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Exploration of coal seams intruded by magmatic body using seismic attribute technology

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Abstract
When a magmatic body intrudes into a coal seam, it dramatically reduces the coal quality, causes the waste of coal resources, and brings hidden dangers to the safe production of the coal mine. Thus, detecting the parts of coal seams intruded by magmatic bodies is extremely important. This paper describes the mechanism of intrusion of a magmatic body into a coal seam and introduces the key steps of Seismic Attribute Technology. After the intrusion of a coal seam by magmatic bodies, seismic attributes such as frequency bandwidth, main frequency-band energy, average instantaneous phase, and root mean square (RMS) amplitude change significantly. Taking the testing project of Haizi Coal Mine in Anhui Province, China, as an example, the accuracy of using Seismic Attribute Technology for detecting the range of magmatic body intrusion into coal seams was confirmed.

Keywords
Seismic attribute; coal seam; magmatic body; geophysical exploration; Haizi Coal Mine.

Introduction

The intrusion of a magmatic body can damage the thickness and structure of coal seams. Some coal seams can even be completely replaced by magmatic bodies, which greatly affects the safe production of coal mines. The main components of geological work at coal mines are identifying the characteristics and distribution of magmatic intrusions and distinguishing magmatic intruding areas from normal coal seams (Arthur, 1999; Cooper et al., 2007; Li, 2014; Chen et al., 2018; Chen et al., 2019).

Substantial research has been performed on detecting magmatic bodies intruding into coal seams, and various exploration techniques have been developed. The traditional methods include a direct prediction method based on combined borehole and logging data. Borehole and logging data can directly reveal the presence, composition, depth, and other information about magmatic bodies with high vertical resolution. Liu et al. (2019) used a resistivity curve and gamma curve for lithology inversion, conferring the ability to predict the presence of a magmatic body. Meanwhile, Li et al. (2020) used a resistivity curve and gamma curve, which were sensitive to magmatic bodies, to reconstruct the density curve and acoustic curve and achieve the prediction of magmatic bodies. However, the costs of borehole and logging methods are high, and they are unsuitable for large-scale implementation. A network of boreholes would also seriously affect the accuracy of detecting magmatic body boundaries. Another approach is geophysical prediction methods based on gravity, magnetism, and electricity. The gravitational method can be used to detect magmatic bodies with strong anomalous fields. The magnetotelluric method (MT) can be used to detect magmatic bodies with large depths and low background fields. The magnetic method can be used to detect magmatic bodies with a large intrusion range and magnetic anomaly. Wang et al. (2015) used the magnetic method to identify the intrusion boundary of magmatic bodies effectively. However, for these traditional geophysical methods, the detection accuracy highly depends on high-quality original data. Under the conditions of large noise and electromagnetic interference, as found in coal mining areas, these methods often have difficulty obtaining good detection results due to the poor quality of the originally collected data.

Seismic data have the advantage that information can be collected intensively on a large scale. Using seismic information, the structure and lithology of a stratum can be studied from multiple angles (Li et al., 2010; Wang et al., 2015; Cheng et al., 2016; Ren et al., 2017; Christopher, 2020; Wu et al., 2020). Many researchers have performed substantial research on the intrusion of magmatic bodies into coal seams by using seismic exploration methods. Wu et al. (2014) used forward modelling to systematically analyze the reflected wave characteristics of areas of magmatic body intruding into coal seams and calculated the law reflecting the change of the reflected wave characteristics in magmatic body intrusion areas. In addition, Zhao et al. (2014) used seismic inversion, seismic facies analysis, and spectral decomposition to explain the distribution range of magmatic bodies. However, when using traditional seismic data interpretation, there are some insurmountable problems, such as the accuracy of seismic data interpretation being affected by the inaccurate selection of reflection horizons, the difficulty in determining the arrival time of the first arrivals, and the lack of data when interpreting along a single horizon.

Using seismic attribute technology, various attributes of the studied strata can be extracted, and various attributes can be studied to explain the structures. Few related studies have focused on predicting magmatic body intrusion into coal seams using seismic attribute technology. This paper briefly describes the mechanism by which magmatic bodies intrude into coal seams and analyzes the seismic attributes of such coal seams. By focusing on the test project in Haizi Coal Mine in Anhui Province, China, the effectiveness of seismic attribute technology for detecting magmatic body intrusion into coal seams is expounded.

Methodology

Mechanism of magmatic body intrusion into coal seams.

The magma is controlled by the stress regimes of the rocks in the intrusion process. The fault structure is the pathway of magma migration, which was formed before the magmatic intrusion. The tensional faults open well, and the lateral pressure is relatively small. They do not cause great stress resistance for the magmatic movement and are favorable for magmatic activity; in particular, it is more favorable for magmatic activity in the deep-cut and extended tensional-torsional faults.

After high-temperature magma has formed deep underground, it flows upward along fracture channels (faults) to reach the coal measure strata. When the resistance of the top surrounding rock is greater than the uplifting pressure surrounding the magma, the magma alters its original direction of movement, intruding horizontally from the parts with larger compressive stress to those with smaller compressive stress. Compared with the harder roof and floor layers, coal seams are generally softer and more layered, making them more susceptible to magma intrusion. With the flow of magma, the pressure is gradually released, and the temperature decreases, after which compound intrusions eventually form, along with rock walls and rock beds on different scales (Fig. 1).

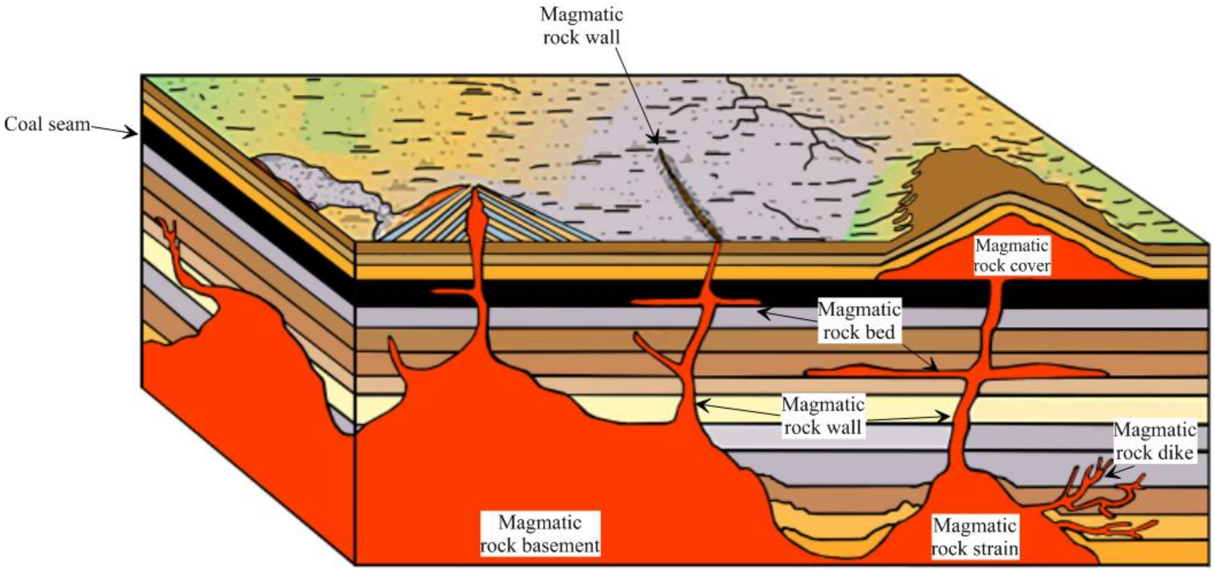

Fig. 1 Schematic diagram of magmatic bodies intruding into a coal seam.

Seismic attribute technology

Conception. Seismic attributes refer to the special measured parameters of geometric, kinematic, dynamic, and statistical characteristics, which can be directly extracted from seismic data or calculated using mathematical methods.

Seismic wave information can reflect the characteristics of underground formations. When the petro-physical properties of subterranean strata change, the characteristics of seismic reflected waves will inevitably change, and then the seismic attributes will also change. When the underground coal seam becomes thinner or when structural anomalies occur, the characteristics of seismic reflected waves will differ from those of normal coal, so the seismic attributes will also differ. This is the theoretical basis for using seismic attributes to predict lithological changes and structural anomalies of coal seams.

Seismic attribute technology refers to the technology that extracts relevant seismic attributes based on seismic data, evaluates them, and is used to solve practical geological problems.

Mechanism of seismic attributes for the identification of magmatic bodies. The characteristics of the seismic waves change significantly when coal seams are intruded by magmatic bodies. For example, the reflected wave group will be obviously interrupted near the boundaries of the magmatic intrusive bodies, and diffraction wave phenomena are often seen on the superposed sections. Also, when magmatic bodies intrude sedimentary rock from the side, it will appear wedge-shaped or beaded, which causes the reflected wave group structure in the sedimentary rock to be inconsistent, as shown in Fig. 2.

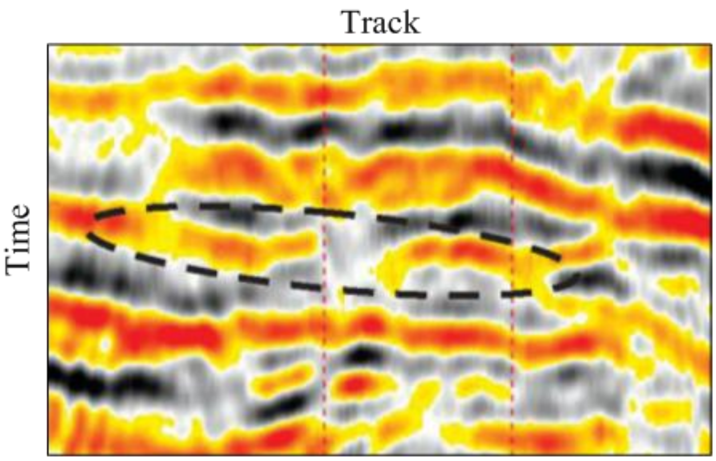

Fig. 2 Characteristics of a magmatic body in a seismic profile

The causes of the aforementioned phenomena can be explained from the viewpoint of the changes in wave impedance as follows: (1) The magmatic body has a great wave impedance value, while the coal bed has a small wave impedance value, and the wave impedance value of the magmatic body is much larger than that of the coal bed; (2) When magmatic body intrudes into a coal seam, the coal seam will become eroded and metamorphic, and the wave impedance of the coal seam will be discontinuous; (3) The lithologic characteristics of the coal seam roofs will be changed.

Due to changes in these wave impedance parameters, the seismic wave energy changes markedly when the intruded part of the magmatic body is in direct contact with the primary coal seam, making the characteristics of the seismic attributes change significantly. Here, the range of magmatic body intrusion can be well reflected by the seismic attributes. This is the geophysical premise of using seismic attribute technology to detect the intrusion of magmatic bodies into coal seams.

Seismic attribute optimization. When the properties of a certain stratum undergo significant change, for example, after the coal seam is intruded by magmatic bodies, each seismic attribute is affected to different degrees. That is when the coal seam is intruded by magmatic bodies to the same degree, different seismic attributes have different sensitivities. To select sensitive seismic attributes from among numerous options, correlation analysis on seismic attributes according to Eq. (1) was performed to determine the correlation coefficient r between each seismic attribute and the problem to be studied (Ni et al., 1999). The larger the correlation coefficient r, the greater the correlation between the attribute and the studied problem.

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \tag{1}$$

Here, x_i is the i-th seismic attribute, $\bar{x}$ is the average value of the i-th seismic attribute under different intrusion degrees, y_i is the percentage of different intrusion degrees and $\bar{y}$ is the average percentage of intrusion degrees.

Normalization of seismic attributes. Due to the different methods of extracting and calculating different seismic attributes, the unit, dimension, numerical size, and variation range of different seismic attributes differ. If these attribute data are used directly, the phenomenon of the attributes with large absolute values being highlighted will suppress the attributes with small absolute values. To avoid this, it is necessary to standardize the selected seismic attribute data.

According to the characteristics of seismic attributes, range normalization is usually used to normalize the seismic attributes in the actual application process. To perform range normalization, we can subtract each observation of an attribute from the minimum value of the attribute and divide the result by the range of observations for that attribute using the following formula:

$$x'_{ij} = \frac{x_{ij} - \min\limits_{1 \le k \le n} x_{kj}}{\max\limits_{1 \le k \le n} x_{kj} - \min\limits_{1 \le k \le n} x_{kj}} \quad (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m), \tag{2}$$

Where, x'_{ij} and x_{ij} are the attribute values after and before transformation, respectively. After normalization, the observed value of each seismic attribute is between 0 and 1, which is beneficial for using these seismic attributes for direct comparison and analysis (Chen et al., 2022).

Table 1. Correlation coefficients between different seismic attributes and degree of magmatic intrusion

Seismic properties	Coefficient	Seismic properties	Coefficient
Frequency bandwidth	0.8920	Instantaneous frequency slope	0.2125
Main frequency-band energy	0.8438	Average amplitude	0.2127
Average instantaneous phase	0.8177	Amplitude value	0.2126
RMS amplitude	0.8081	Mean absolute amplitude	0.2063
Main frequency	0.7047	Relative amplitude	0.1802
Main frequency amplitude	0.7981	Average instantaneous frequency	0.1396
Crest amplitude	0.6630	Average crest amplitude	0.1211
Maximum amplitude	0.5920	Total absolute amplitude	0.0993
Trough amplitude	0.5523	Average maximum crest amplitude	0.0558
Waveform positive half-cycle energy	0.4367	Amplitude change	0.0502
Time domain average energy	0.4250	Shaft center amplitude	0.0450
Broadband total energy	0.3310	Shaft center frequency	0.0230

As presented in Table 1, four seismic attributes with relatively large correlation coefficients with the degree of magmatic intrusion are selected: frequency bandwidth, main frequency-band energy, average instantaneous phase, and RMS amplitude.

Forward numerical simulations

Due to the different thicknesses of magmatic body intrusions in coal seams, the changes in seismic attributes caused by the intrusions of a magmatic body in some areas may be manifested in the weakening of the reflected wave energy, disordered event axis, and the deterioration of the seismic data quality. This could result in major difficulties in the interpretations of the seismic data. Therefore, studying the response characteristics of seismic attributes will potentially help identify the ranges of the coal seams intruded by magmatic bodies from the seismic data and improve the accuracy of the seismic data interpretations.

To verify the result from the section "Normalization of seismic attributes" on the selection of the seismic attributes that are the most sensitive to the intrusion areas of the magmatic body, a model with the original coal, coke, and magmatic body was designed. Then, forward modelling was carried out to analyze the seismic responses of the reflected wave of the forward modelling model. The forward model utilized in this study is detailed in Fig. 2. The width of the model was 5,000 m, the depth was 600 m, and the main frequency of the seismic wavelet was 50 Hz.

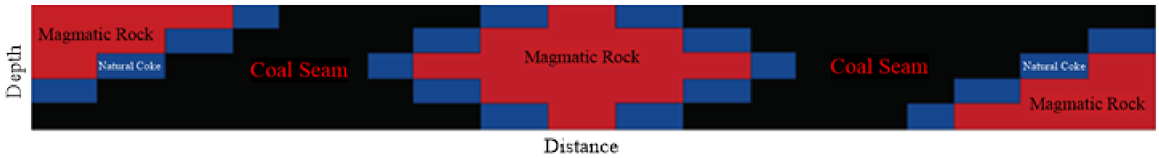

Fig. 3 Forward model of a coal seam intruded by magmatic body

The physical parameters in the model are shown in Table 2.

Table 2. Physical parameters of a forward model

Lithology	Density ($g\cdot cm^{-3}$)	Vp ($m\cdot s^{-1}$)	Vs ($m\cdot s^{-1}$)	Thickness (m)
Mudstone	2.4	3000	1400	
Coal Seam	1.4	2200	960	0~5
Natural coke	1.7	2500	1200	
Magmatic body	2.9	5500	2800	0~5

Combined with previous studies of other scholars (Wu et al., 2015; Christopher, 2020; Shan et al., 2020), we selected the energy-type attributes and amplitude-type attributes that are more sensitive to magmatic bodies for numerical simulation. The frequency bandwidth (Calculated coefficient is 0.8920), main frequency-band energy (Coefficient: 0.8438), average instantaneous phase (Coefficient: 0.8177), RMS amplitude (Coefficient: 0.8081), trough amplitude (Coefficient: 0.5523), and average crest amplitude (Coefficient: 0.1211) of the simulated results were then analyzed. The geological model (Fig. 3) was numerically simulated, and the results (after normalization) are shown in Fig. 4.

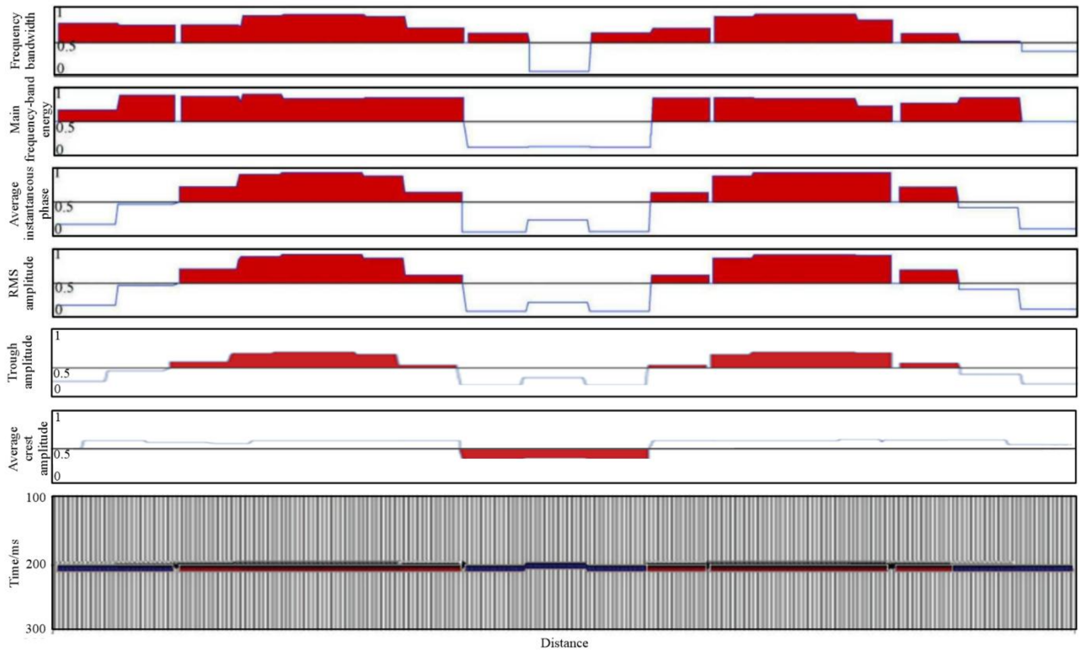

Fig. 4 Consequences of the forward modelling analysis

In the present investigation, an intersection analysis technique was used to examine the attributes, thicknesses, and positions of the magma intrusions. The forward numerical simulation results revealed the following:

(1) The frequency bandwidth, main frequency-band energy, average instantaneous phase, and RMS amplitude were found to be sensitive to the responses of the magmatic body, i.e., the value of these seismic attributes increased with the degree increment of magmatic body intrusion. Meanwhile, the amplitude of trough amplitude only reached about half of the first four attributes, while the amplitude polarity of the average crest amplitude was opposite to other properties

(2) As the thickness of the magmatic body increases, the amplitude of each seismic attribute gradually decreases; when the coal seam is completely eroded by the magmatic body, these amplitudes increase significantly.

(3) When the magmatic body intrudes into the coal seam at different locations, the seismic attributes are different. When the magmatic body intrudes from the middle part of the coal seam, the changing amplitude of seismic attributes is larger, while when the magmatic body intrudes from the bottom part of the coal seam, the changing amplitude of seismic attributes is smaller.

Therefore, the results of this forward modelling successfully confirmed the feasibility of using seismic attributes to detect the intrusion ranges of magmatic bodies in coal seams (Wu et al., 2020).

Case study

To verify the effectiveness of seismic attribute technology in identifying the extent of magmatic body intrusion into a coal seam, a test project was carried out in Haizi Coal Mine, Anhui Province, China.

Overview of the study area

Haizi Coal Mine is located in Suixi County, in the northern part of Anhui Province, belonging to the Huaibei coalfield. Its geographical coordinates are 116°34′37″–116°41′25″E, 33°40′44″–33°43′31″N (Fig. 5). Figure 5c shows the distribution of boreholes in the study area. Notably, before the start of the test project, there were only three boreholes in the study area, namely, Z9, Z10, and G43. After the completion of the test project, boreholes J1–J7 were produced.

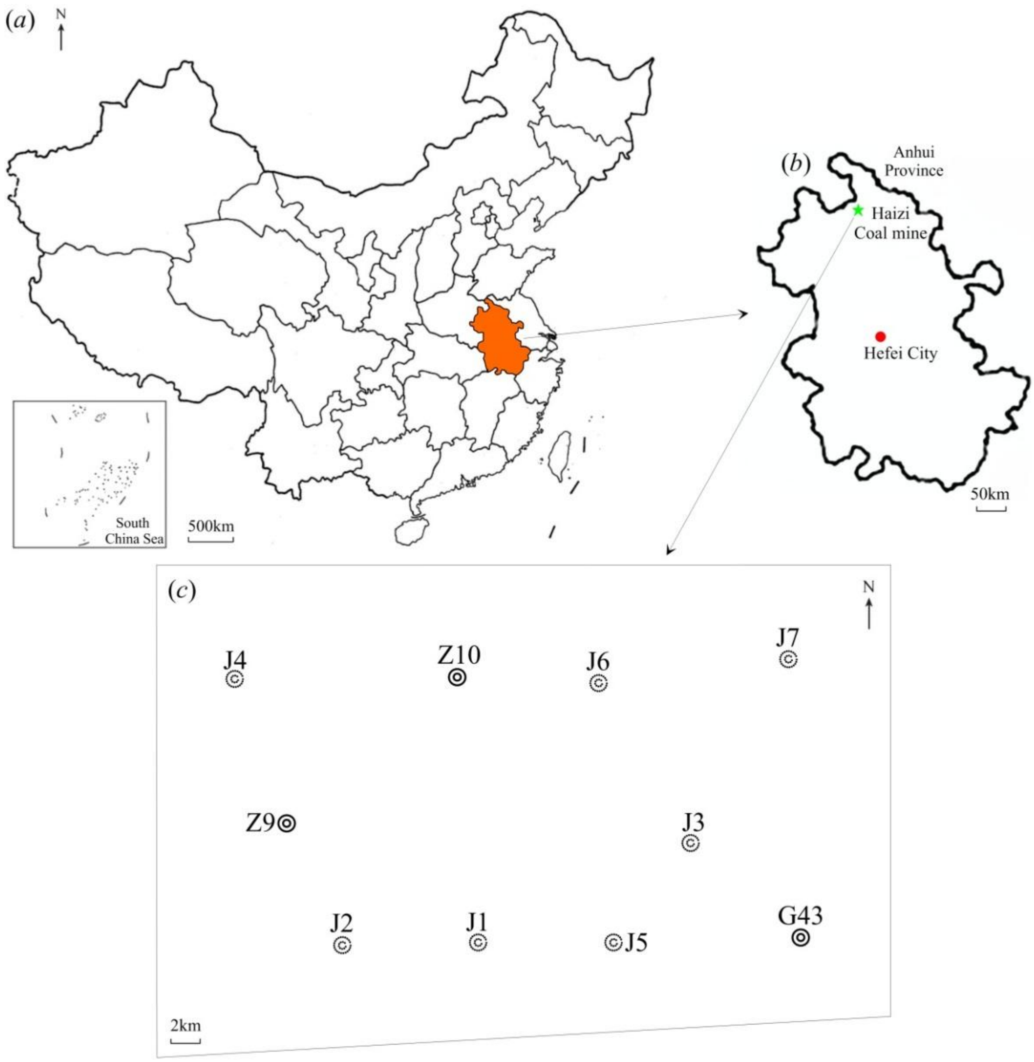

Fig. 5 Location of the study area.

The coal-bearing strata in the study area are Carboniferous–Permian, containing four mineable coal seams, namely, Nos. 7, 8, 9, and 10 coal seams, in the Lower Permian (Table 3). Of them, No. 9 coal seam is the main one currently being mined. This seam is 1.00–7.97 m thick and is 58–107 m away from the No. 10 coal seam below it.

Table 3 Generalized stratigraphy of Haizi Coal Mine

Erathem	System	Series	Formation	Thickness (m)	Rock description
Paleozoic	Permian	Lower	Lower Shihezi Formation	16.05	Diorite
				4.24	Siltstone
				120.00	Diorite
				2.50	Mudstone
				17.18	Siltstone
				2.32	Mudstone
				8.60	Siltstone
				6.03	Sandstone
				3.29	Mudstone
				8.03	Siltstone
				6.88	Mudstone
				2.00	No. 7 Coal Seam
				5.12	Mudstone
				9.64	Sandstone
				7.14	Mudstone
				1.40	No. 8 Coal Seam
				3.10	Mudstone
				2.43	No. 9 Coal Seam
				1.97	Mudstone
				4.04	Sandstone
				4.60	Mudstone
				2.63	Sandstone
				2.16	Siltstone
			Shanxi Formation	1.41	Sandstone
				2.63	Siltstone
				6.20	Sandstone
				8.65	Siltstone
				3.57	Sandstone
				23.49	Siltstone
				20.77	Sandstone
				1.15	Siltstone
				2.67	No. 10 Coal Seam
				4.56	Siltstone
				25.50	Sandstone

Analysis of seismic response characteristics

In the study area, the intrusion of magmatic bodies into the No. 9 coal seam is the most serious, which mostly involves lateral bedding erosion. After the intrusion of a coal seam, its physical properties change significantly, and the characteristics of the seismic reflection waves formed also differ.

Before the test project, we first analyzed the three boreholes (Z9, Z10, G43) present in the study area. At borehole Z9, the thickness of the No. 9 coal seam was 2.28 m. No natural coke or magmatic body was found (Fig. 6a). At borehole Z10, the structure of the No. 9 coal seam was natural coke (1.89 m) + coal (0.45 m) (Fig. 6b). Finally, at borehole G43, the structure of the No. 9 coal seam was basalt (1.72 m) + coal (0.53 m) (Fig. 6c). These three figures show that, on the seismic time profiles, the reflected wave energy of the coal seam is clearly strong. The continuity is good when it is not intruded by the magmatic body (Fig. 6a). However, after the intrusion of the coal seam, the reflected wave energy in the magmatic body intrusion area is clearly weakened, the reflected wave is disordered, the continuity deteriorates, and the amplitude is weakened or lost completely (Fig. 6b and 6c).

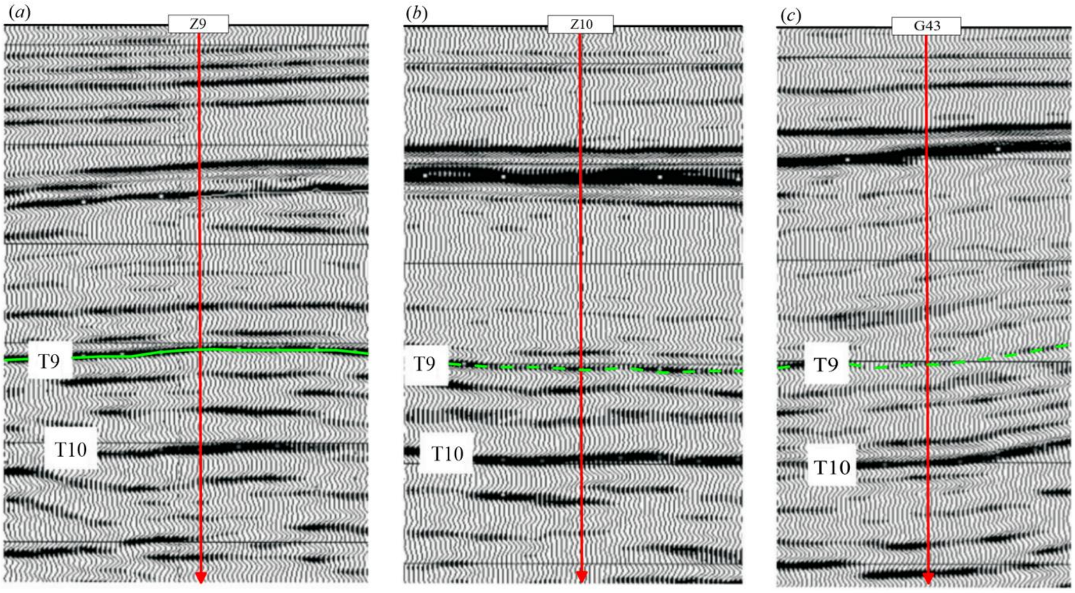

Fig. 6 Seismic time profiles of each borehole. The green line indicates the location of coal seam 9. In Fig. 6a, the non-intruded coal seam is indicated by a solid line. In Figs. 6b and 6c, the intruded coal seams are indicated by dotted lines.

Seismic attribute interpretation

Based on the optimization of seismic attributes mentioned above, there are relatively clear differences in seismic attributes such as frequency bandwidth, main frequency-band energy, average instantaneous phase, and RMS amplitude of coal seams in the areas with and without magmatic intrusion.

Combined with the intrusion of magmatic bodies into coal seams as revealed by boreholes in the study area, the above seismic attributes were extracted and normalized for the reflected waves of the No. 9 coal seam in the seismic data of the study area. As shown in Figs. 7a-7d, the black boreholes revealed normal coal seams, while the red boreholes revealed magmatic bodies.

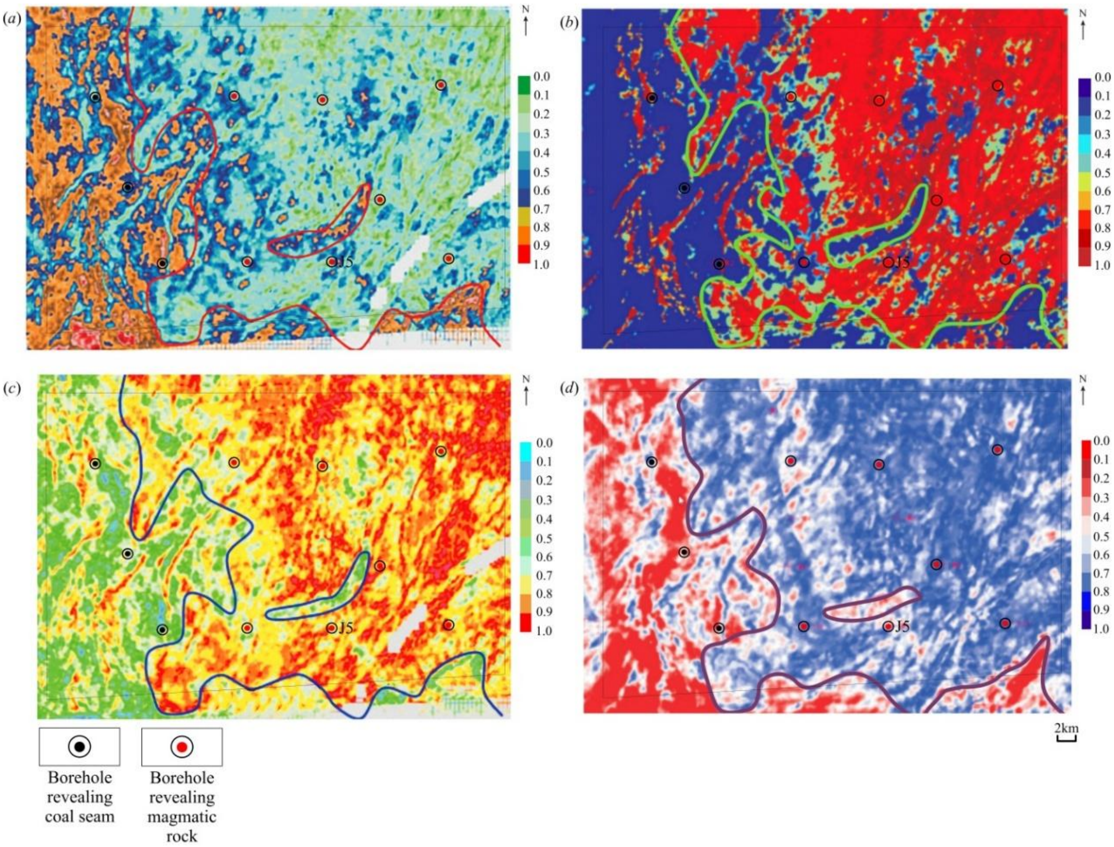

Fig. 7 Maps of Seismic attributes of the reflected wave of the No. 9 coal seam. (a) frequency bandwidth; (b) main frequency-band energy; (c) average instantaneous phase; (d) RMS amplitude.

As shown in Fig. 7a, the change of colours (green–blue–yellow–orange) indicates the value of frequency bandwidth from low to high. The normal coal seam is represented by orange. The frequency bandwidth reflected in the coal seam area has a high value (>0.7), while the frequency bandwidth of the magmatic body intrusion area shows a low value. Using the frequency bandwidth attribute, the range of the normal coal seams and the magmatic intruding areas is delineated (the red line is the dividing line).

As shown in Fig. 7b, the change of colours (blue–cyan–yellow–red) indicates that the value of the main frequency-band energy is from low to high. The normal coal seam is represented in blue. The main frequency-band energy reflected in the coal seam area has a low value (<0.2), while the frequency band of the area with the intrusion of the magmatic body shows a high value. Using the main frequency-band energy attribute, the range of the coal seam and magmatic body intrusion areas is delineated (the green line is the dividing line).

As shown in Fig. 7c, the change of colour (cyan–green–yellow–red) represents the value of the average instantaneous phase from low to high. The normal coal seam is represented by green and cyan. The average instantaneous phase reflected in the coal seam area has a low value (smaller than 0.4), while that in the intrusive area of the magmatic body shows a high value. Using the average instantaneous phase attribute, the range of the coal seam area and the intrusion area of the magmatic area is delineated (the blue line is the dividing line).

As shown in Fig. 7d, the change of colour (navy blue–blue–white–red) indicates the value of RMS amplitude from low to high. The normal coal seam is represented by white and red. The RMS amplitude reflected in the normal coal seam area has a high value (larger than 0.6), while that of the magmatic intrusion area shows a low value. Using the RMS amplitude attribute, the coal seam and magmatic body intruding areas are delineated (the pink line is the dividing line).

Accuracy analysis

The range of magmatic bodies intruding into coal seams is predicted based on seismic attribute technology. Before the test project, there were only three boreholes in the study area. After the project, seven more confirmatory boreholes, namely, J1–J7, were implemented, as shown in Fig. 8. The black boreholes did not expose magmatic bodies, and the red boreholes did.

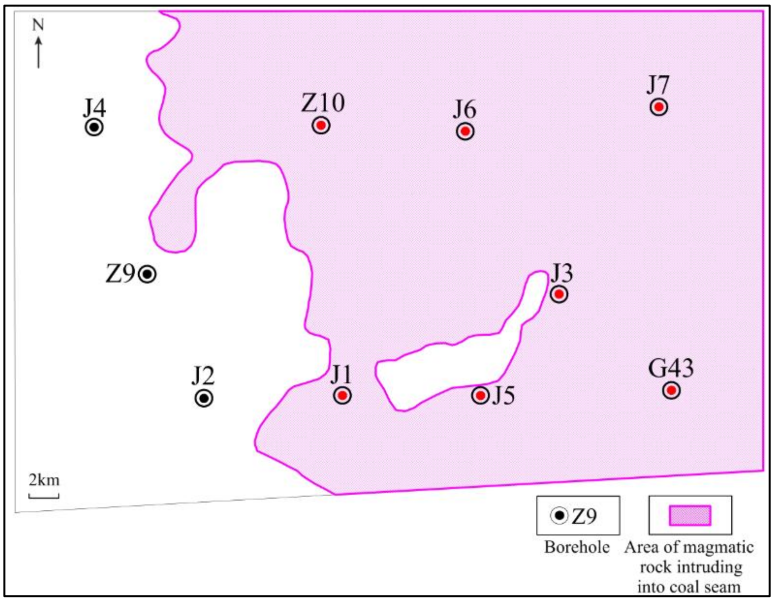

Fig. 8 Schematic diagram of the area of magmatic body intruding into the coal seam.

Table 4 summarizes the verification of the boreholes. It can be seen that boreholes J2 and J4 revealed normal coal seams, while boreholes J1, J3, J5, J6, and J7 revealed natural coke or magmatic bodies, which are located in the areas with the intrusion of magmatic body. The obtained findings indicate the feasibility of using seismic attribute technology to delineate the range of magmatic bodies intruding into coal seams.

Table 4. Statistics of boreholes

Borehole Number	Lithological characteristics of No. 9 coal seam (thickness)	Illustration
Z9	Coal (2.28 m)	Normal coal

Z10	Natural coke (1.89 m) + Coal (0.45 m)	In a magmatic intruding area
G134	Basalt (1.72 m) + Coal (0.53 m)	In a magmatic intruding area
J1	Natural coke (1.25 m) + Coal (0.93 m)	In a magmatic intruding area
J2	Coal (2.32 m)	Normal coal
J3	Basalt (0.92 m) + Coal (1.28 m)	In a magmatic intruding area
J4	Coal (2.10 m)	Normal coal
J5	Basalt (1.13 m) + Coal (0.89 m)	In a magmatic intruding area
J6	Natural coke (1.67 m) + Basalt (0.21 m) + Coal (0.39 m)	In a magmatic intruding area
J7	Natural coke (1.81 m) + Basalt (0.16 m) + Coal (0.36 m)	In a magmatic intruding area

Conclusions

This paper proposes a method for detecting the range of coal seams intruded by magmatic bodies by using seismic attribute technology. Based on the analysis of an engineering example, the following conclusions can be drawn: After a magmatic body intrudes into a coal seam, there is a great difference in physical properties between the coal seam and the area where the magmatic body has intruded. Using seismic attribute technology to predict the intrusion range of magmatic bodies is feasible and effective. Since there is no one-to-one correspondence between various seismic attributes and underground geological targets, various geological anomalies may cause the same changes in a certain attribute. It is difficult for attribute predictions to match the actual stratigraphic conditions fully. Various attribute values can be matched with different weight factors, and weight factors can be added to predict where the magmatic body has intruded into a coal seam. This can be synthesized into a total value for comparison and analysis and comprehensively analyzed with the attributed research of other geological anomalies to improve predictive accuracy.

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