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Prediction of coal mine water hazards: a case study from the Huainan Coalfield

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Abstract
In the Huainan Coalfield of China, the hazards posed by mine water are becoming more serious with increasing mining depth. Groundwater is mainly transported through tectonic fractures in coal measure strata. Therefore, the identification of fractures in coal measure strata aids in determining whether or not a target coal seam will suffer water hazards. Here, we introduce a prediction method of mine water hazards based on the comprehensive analysis of seismic and logging data using the Permian coal strata of the Huainan Coalfield in China. We used seismic data to locate tectonic fractures, and then selected an appropriate place to drill an exploration well, where dipole acoustic logging data were utilized to finely predict the strata with relatively well-developed fractures. Finally, according to the prior knowledge of the hydrogeology and water inrush of the upper mined coal seams, we concluded that the target strata were likely to contain groundwater and would aggravate the hazard posed by water inrush when the under-group coal seams were mined.

Keywords Mine water inrush · Coal measure strata · Tectonic evolution · Dipole acoustic logging · Fracture prediction · Seismic data

Introduction

Water inrush has been one of the main causes of disasters threatening coal mining. With the increase of the coal mining depth, the problems posed by water inrush are becoming more serious across China. Unlike many coal mines in other countries, 90% of coal mine water inrush accidents in China have been caused by karst water flowing into coal measure strata. The main karst aquifers in China are found within Ordovician limestones, where tectonic and dissolution fractures, dissolving pores, karstic caves, and karst collapse columns are not only well-developed but are also interconnected with one another. Worsening this situation, small, karst conduits with high water contents and permeability exist locally, which are likely to lead to large-scale water inrush disasters (Gui et al. 2017; Huang et al. 2009; Li et al. 2015; Luo et al. 2016).

In China, more than half of all coal reserves come from Permian and Carboniferous coal seams. They are distributed above Ordovician limestones of 200–800 m in thickness, bringing great risks to coal mining operations (Han et al. 2009; Zhang 2005). Additionally, surface water and phreatic water can also cause water inrush. To prevent water inrush, discerning the forms of water conduits is very important. Water conduits, such as faults, fractures, karstic caves, karst pipelines, karst collapse columns, and unclosed boreholes, play an important role in transporting water into coal measure strata (Li and Li 2014). Approximately 80% of the large-scale water inrush disasters in China have been caused by karst water flowing through fracture zones (Huang et al. 2014).

For unexploited coal measure strata, the fault and fracture zones developed in the strata are the main water inrush conduits, which cause shallow phreatic waters and deep artesian waters to migrate and penetrate into coal measure strata (Huang et al. 2014). Meanwhile, coalbed methane (CBM) in pores and fractures also presents a potential hazard to coal mining. However, reasonable exploitation and utilization can result in the production of effective, clean energy (Flores 1998). The existence of groundwater and CBM is mainly caused by the fractures in coal measure strata, which are affected by the porosity and permeability of the host rock. The degree to which fractures are developed determines the permeability of coal measure strata (Chaimov et al. 1995; Chen

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and Tang 2013). Therefore, the prediction of fracture development zones in coal measure strata is of great importance to the prevention of coal mine water inrush and the exploration of CBM.

The natural fractures in coal measure strata can be divided into two types according to their origin: endogenous fractures (or primary fractures) and exogenous fractures (or secondary fractures). Endogenous fractures are the product of coal metamorphism, and their degree of development is closely related to the strength of crustal stress and the type of metamorphism. Exogenous fractures, which are closely related to fold or fault structures, are caused by crustal stress with no significant dislocation or displacement rupture in the coal measure strata (Wang et al. 2003); tectonic fractures are one kind of exogenous fracture. In the coal-bearing strata in China, systems of tectonic fractures are the main reservoirs and seepage conduits for groundwater. Where tectonic fractures are relatively well-developed in coal measure strata, groundwater is more likely to seep and accumulate, thus forming aquifers and threatening the safe production of coal mines. Therefore, predicting the development of fractures in coal measure strata is also very important for the identification of aquifers.

For many years, geophysical methods have been widely applied to assess the development and distribution of aquifers. To determine the location, characteristics, and flow paths of aquifers, one or several geophysical methods have been adopted in previous studies (Aizebeokhai et al. 2016; Bernard and Legchenko 2003; Fechner et al. 2017; Hanafy 2013; Heinson et al. 2010; Leeming et al. 2001; Manzi et al. 2012; Legchenko et al. 2003; Ulugergerli et al. 2007; Vincenz 1968). In some cases, the comprehensive application of geological and geophysical methods to groundwater exploration will obtain very good results (Pettifer and Wood 2004). Additionally, geophysical methods play an important role in addressing groundwater issues, such as seawater intrusion and aquifer management (Abraham et al. 2010; Farrell et al. 2005). However, most research has been focused on shallow aquifers, while few have investigated deep aquifers. In the process of groundwater exploration, fractures storing or conducting groundwater have been selected as targets in many studies to determine the existence of groundwater. Similarly, we also chose such fractures as targets and comprehensively applied geophysical logging and seismic analyses to explore a deep aquifer.

In this study, we analyzed the seismic and dipole acoustic logging data in the Guqiao mining area of the Huainan Coalfield in China to predict water hazards in the coal measure strata. First, we used high-resolution 2D seismic data to finely resolve the faults that may transport water to initially determine the location and approximate azimuth of the fractures acting as groundwater seepage conduits. We then selected the location of an exploration well under the constraints of its tectonic evolution. Based on the shear wave splitting phenomenon recorded by dipole acoustic logs, we determined the location, development, and orientation of the fractures in the coal measure strata. Eventually, using the prior knowledge of the hydrogeology and water inrush in the upper work faces, we also determined the potential mine water hazard and its mechanism.

Geologic and hydrogeologic setting

Geologic background

The Guqiao mining area of the Huainan Coalfield is located on the southern margin of the North China Plate, the neotectonic movements of which mainly occurred during the Indosinian and Yanshanian periods. The tectonic movements during the Indosinian period produced many folds and fractures, and the direction of tectonic stress was approximately south–north (S–N). During the Yanshanian period, fewer folds developed, but faults striking east–west (E–W) were better developed.

The northwest-trending Guiji syncline, which contains a high density of faults and a complex structure, is located slightly north of the center of the Guqiao mining area. The secondary folds in its axial portion are well-developed, and the dip of these folds reaches 18°. Except for this area, the other parts of the coal measure strata slope gently, with the dips ranging between 5 and 8°. Figure 1, drawn on the basis of 3D seismic data for the target area, displays the fault system. We mainly studied fault FD108 and the development of its surrounding fractures. Well B7, which lies on the 2D measuring line that intersects fault FD108, was drilled orthogonal to the fault. As is shown in Fig. 1, well B7 forms a right triangle with the 2D measuring line and fault FD108. Later, dipole acoustic logging was performed.

According to the drilling data of well B7 (Fig. 2), the well depth ranges from 0 to 1062.92 m. The component strata (from oldest to youngest) consist of the following: (1) Carboniferous strata, with thin coal seams, mainly consisting of mudstones and medium and fine sandstones, and exhibiting no mining value; (2) the Permian Shanxi Group, which mainly consists of coal seam 1; (3) the Permian Lower-Shihezi Group, mainly consisting of coal seams 8 and 6; (4) the Permian Upper-Shihezi Group, which mainly consists of coal seams 13-1 and 11-2; and (5) Quaternary strata, 230–500 m in depth and mainly consisting of clay, sandy clay, and sandstone. Interbedded sandstone and mudstone is the main lithology among neighboring coal seams. At present, coal seams 6 and 1 have not yet been mined. To realize a safe production of coal, prevent water inrush in the mine, and ensure the safe mining of coal seams 6 and 1, the strata targeted for study here were those below coal seam 1 and above coal seam 6, with depths of 950–990 m (the yellow portion of Fig. 2).

Fig. 1 Study area and the local fault system
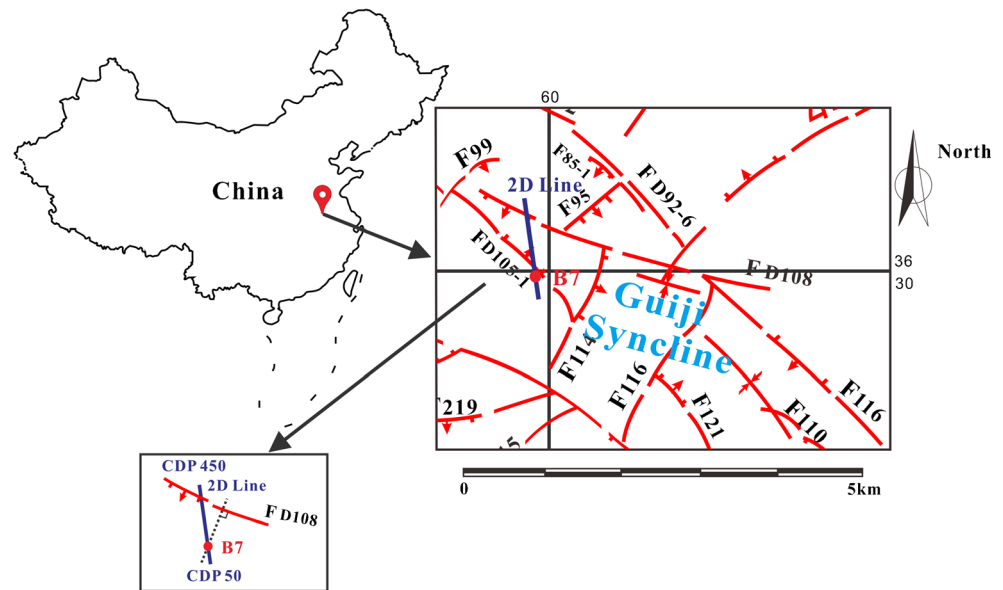
Hydrogeologic background

According to prior hydrogeological knowledge, the aquifers of the Guqiao mining area consist of pore water in a Cenozoic-age unconsolidated sand layer, fissure water in Permian sandstones, and karst fissure water in limestones.

Cenozoic loose aquifer

The Cenozoic sediments directly overlying Permian coal measures are 224.10–576.00 m in thickness and contain four aquifer groups and four water insulation groups, which are distributed within Quaternary and Neogene strata.

Permian sandstone fissure aquifer

The Permian sandstone aquifer is mainly composed of medium- and fine-grained sandstone, with minor components of coarse sandstone and quartzite. They are distributed between coal seams and pelitic rocks. The lithological characters are diverse, and the thickness is quite variable. There are many argillaceous and calcite cements and few siliceous cements. Fractures are unevenly developed and opened, and are generally infilled with calcareous components.

Limestone aquifer

The limestone aquifer mainly consists of limestone karst fissure aquifer groups, and the Carboniferous limestone aquifer mainly consists of confined artesian water. The strata are 99.99–108.70-m thick, with a mean average thickness of 104.48 m. They are comprised of limestone, mudstone, siltstone, and thin coal seams. There are 12–13 layers of limestone, with a mean average thickness of 47.7 m, and the limestone constitutes 44% of the total thickness of these strata. There are more leakage points in shallow limestones than in deep limestones.

Ordovician aquifer

The Ordovician aquifer is mainly composed of limestone karst fissure aquifer groups. From a regional perspective, the karstic Ordovician limestone is better developed in the middle and lower layers. Due to the uneven development of karstic fractures, the abundance of water at different locations differs greatly. The abundance of water in the Ordovician limestone within the Guqiao mining area is characterized as medium.

Generally, during the coal mining process, fault zones are often avoided to prevent collapse. However, if the fault zone is not infilled by carbonaceous or argillaceous cements, even if the zone is shunned, groundwater may still be able to enter the coal measure strata through faults, and stay or circulate within the fractures. Up to this point, coal seams 13-1, 11-2, and 8 in the Permian strata of the study area have been mined. During the mining of these coals, water has been found in the coal measure strata, suggesting that groundwater in the study area can enter the coal measure strata through conduits, such as fractures and fault zones. If there are also water conduit systems in the surrounding rock of coal seams 6 and 1, water inrush will undoubtedly occur during the mining of the two seams. Additionally, groundwater and CBM are concurrent within coal measure strata. If the coal seams are excavated, the discharge of water will lead to desorption of the adsorptive CBM and to further

Fig. 2 Generalized stratigraphic chart of well B7 of the Guqiao mining area (adapted from the Huainan Coal Mining Group)
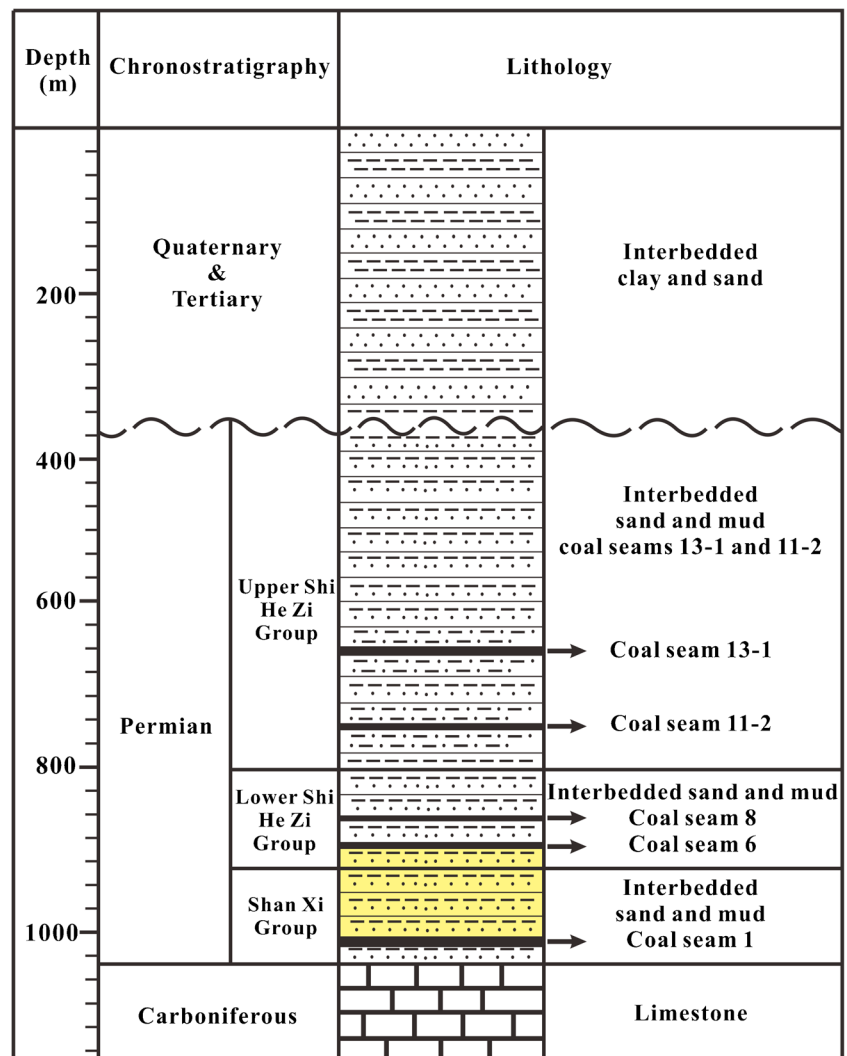
accidents, such as a gas explosion. Therefore, it is very important to predict the fractures in the strata that host coal seams 6 and 1.

Methods

Work flow

In this study, we analyzed the tectonic evolution of the study area using 2D seismic data to identify the areas where fractures may be developed. The positions of the faults were obtained through the interpretation of 2D seismic structures. If the faults penetrate the shallow strata and extend into the phreatic zone, the water in the phreatic zone could be transported to the roofs and floors of coal seams. If the faults run through the deep Carboniferous and Ordovician strata, the confined karst water in the limestone could be led upward to the

roofs and floors of the coal seams. The fractures near the fault zones assist in groundwater migration. Such fractures were the targets of groundwater prediction. Afterward, a recovery technique was employed to model the paleogeomorphology of the Neogene base and coal seams 13-1, 11-2, 8, 6, and 1. Thus, the formation mechanism of the faults and the areas where the fractures may be developed could be understood. Moreover, we could also determine which tectonic movement contributed to the development of seepage fractures, and design an exploratory well to finely resolve them.

It is too risky to drill a well in a fault zone because it might jam the drilling tool. Therefore, the well in this study (well B7) was drilled at a distance from the fault zone. Acoustic dipole logging was then performed and shear-wave detection was conducted for the target strata. In fracture zones, shear waves will be split into fast and slow waves, with polarizations that are parallel and vertical to the fracture planes, respectively.

Fig. 3 Flow chart for water hazard prediction. DTS, shear wave velocity; S1, fast shear waveform; S2, slow shear waveform; V_{S1}, fast shear wave velocity; V_{S2}, slow shear wave velocity
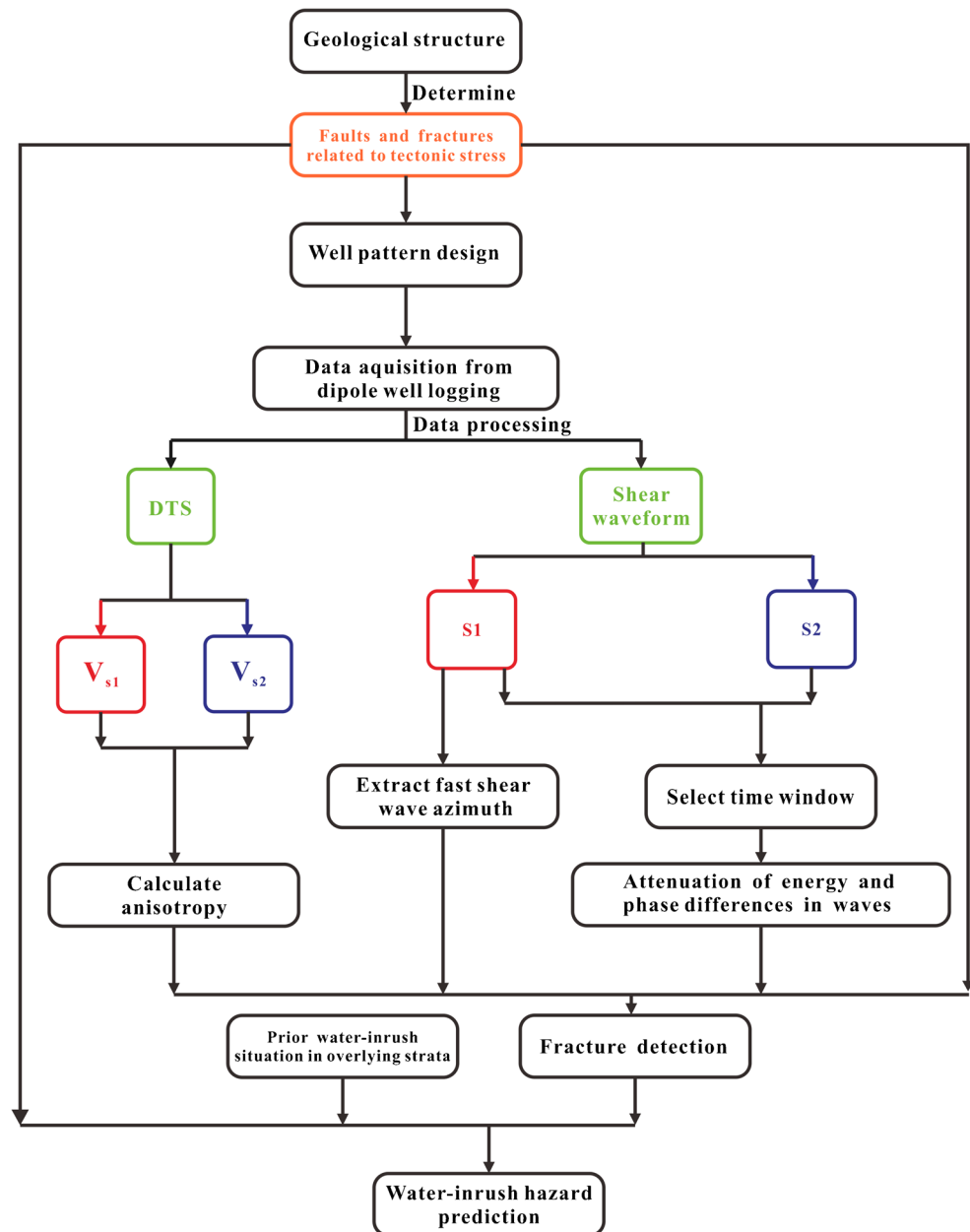
The anisotropy degree of a given stratum (ANI, the fractional difference between the velocities of fast and slow shear waves) was used to reflect the degree of fracture development (Tsvankin 1997). Finally, under the constraints of the prior knowledge of the hydrogeology and water inrush in the shallow mined coal seams, the abundance of water in the target strata could be predicted. The workflow for water hazard prediction in this study is shown in Fig. 3.

Compared with conventional monopole logging, by using dipole acoustic logging, shear waves in both unconsolidated and consolidated strata can be directly measured (Chen 1988). The distance of the acoustic source of the shear wave from this sound emitter is symmetrical, with a center frequency of 8000 Hz. The acoustic wave transducer, with the merits of wide response band, good low-frequency response, and a large dynamic range of acquired signals, cannot only obtain subtle information about fractures (e.g., the relative slowness of fast and slow shear waves and the fast shear wave polarization angle) but also record fairly complete waveforms (Esmersoy et al. 1994).

Shear wave splitting

Shear wave splitting is very sensitive to anisotropy. Many rocks are effectively anisotropic for the transmission of shear waves (Crampin et al. 1984a, b). Fractures in rocks are most commonly anisotropic because the maximum compressive stress in the Earth's crust is generally horizontal, while
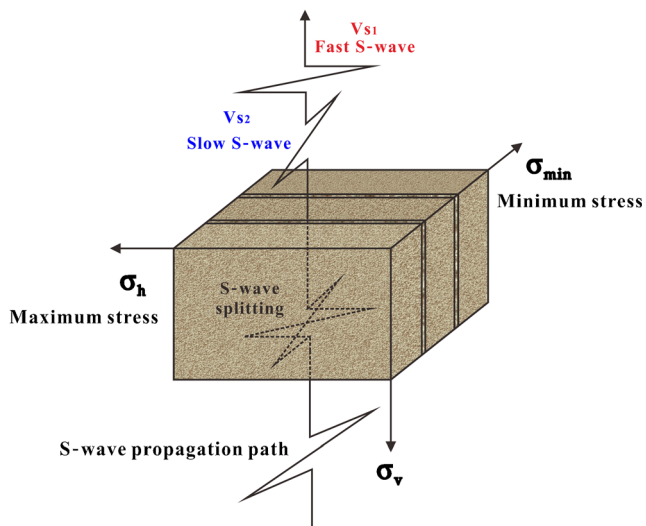
Fig. 4 Shear wave splitting in the horizontally transverse isotropy (HTI) medium

fractures are usually vertically aligned and strikes are parallel to the direction of compressive stress (Hubbert and Willis 1957). Here, a horizontally transverse isotropy (HTI) medium was used to describe the splitting of shear waves (Fig. 4) in the vertical fractures formed by the above horizontal stress. The HTI medium, caused by parallel vertical fractures, micro-fractures, or orientated pores, is a typical azimuthal anisotropic medium (Crampin 1989). According to the dependence of strain on stress, the fracture strike is vertical to the direction of the minimum stress (σ_{min}) on the strata and parallel to the direction of the maximum stress (σ_h). When shear wave polarization crosses the fracture azimuth obliquely, the shear

wave will be split into two mutually orthogonal components, a parallel fracture azimuth and a vertical fracture azimuth. The shear component of the parallel fracture azimuth is transmitted with a high velocity (V_{S1}), and is thus called a "fast" shear wave. The shear component of the vertical fracture azimuth is transmitted with a low velocity (V_{S2}), and is therefore called a "slow" shear wave. The velocity V_{S1} is higher than V_{S2}, and this phenomenon is shear wave splitting (Bush and Crampin 1987; Winterstein 1992). Analyzing fast and slow shear waves is the most direct and reliable means of studying fracture strike and development.

Results and discussion

Tectonic evolution

The formation of fractures is closely related to tectonic stress (Hardy and Ford 1997; Mueller 1995; Nelson 1985; Strayer and Hudleston 1997). The results of studies in the Sichuan Basin by Wang et al. (2016) demonstrated that the direction of fracture development is related to the fault and its tectonic location. For fractures near a fault, the closer they are to the fault, the more closely their directions parallel the fault strike (Wang et al. 2016). Faults and their associated collapses and fractures could lead surface waters and karst waters in the Carboniferous limestone in the study area into coal measure strata and thereby prompt water inrush in the roofs and floors of coal seams. Therefore, the circulation of water is closely linked with tectonic development.

Fig. 5 Impedance profile, with fault numbers 1–4, coal seams 13-2, 11-2, 8, 6, and 1, and the bottom of Quaternary and Tertiary stratum Q4
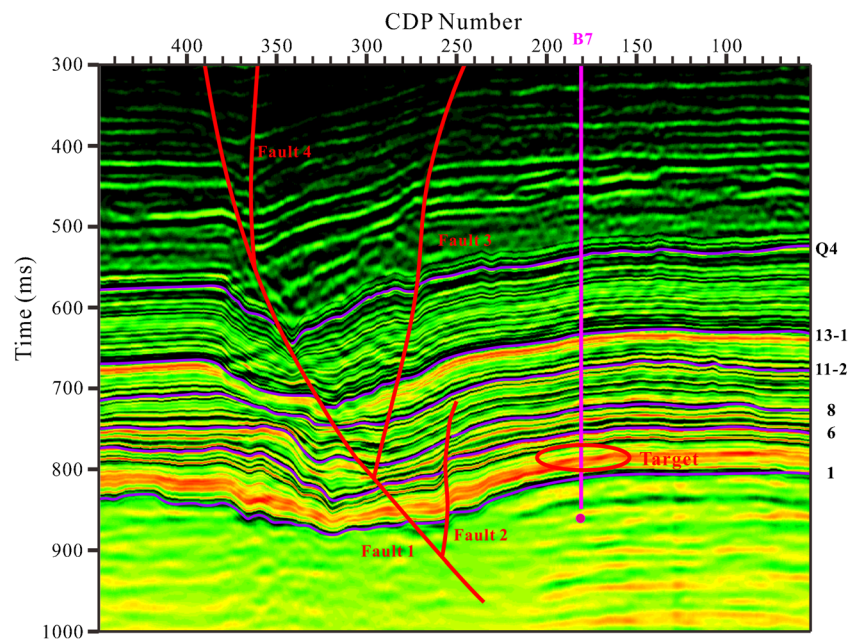
Fig. 6 Flatted impedance profile of coal measure strata. **a** Quaternary and Neogene strata. **b** Coal seam 13-1. **c** Coal seam 11-2. **d** Coal seam 8. **e** Coal seam 6. **f** Coal seam 1
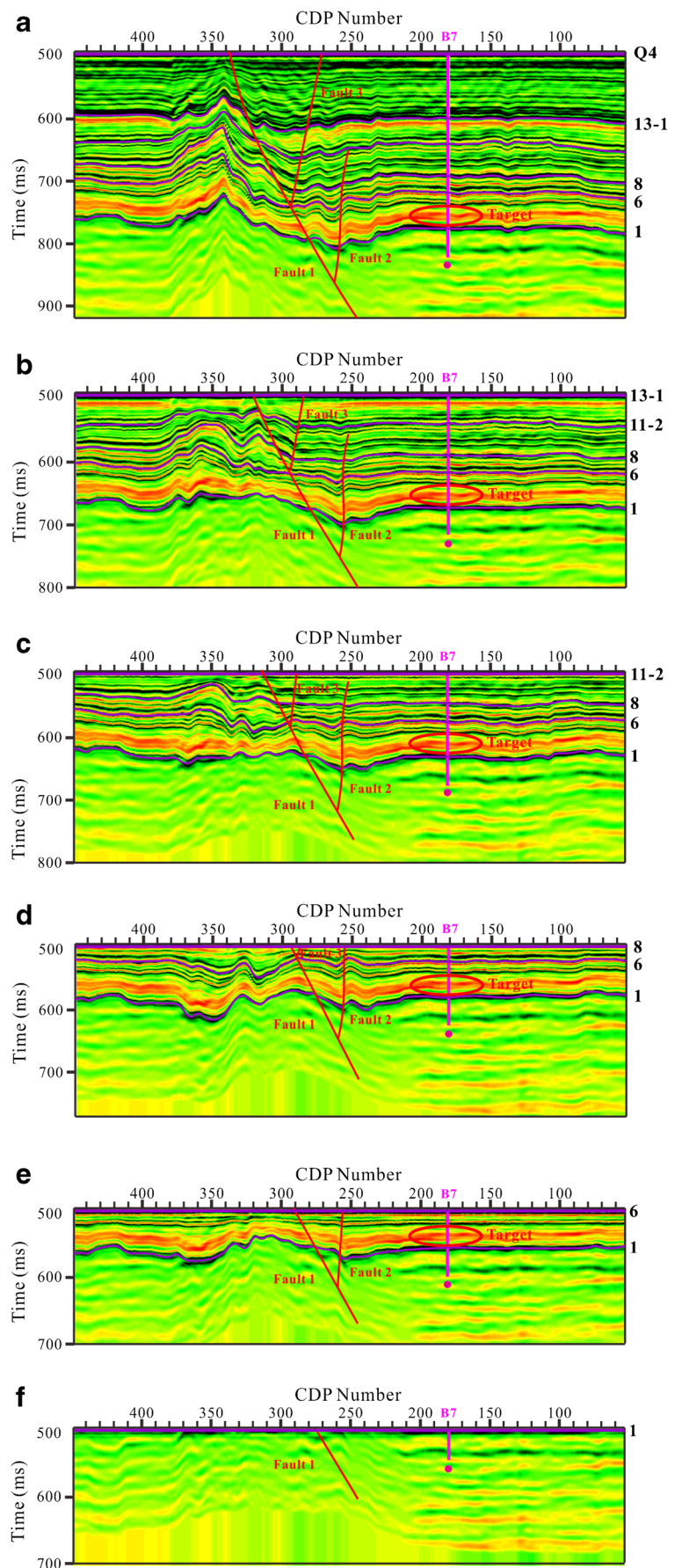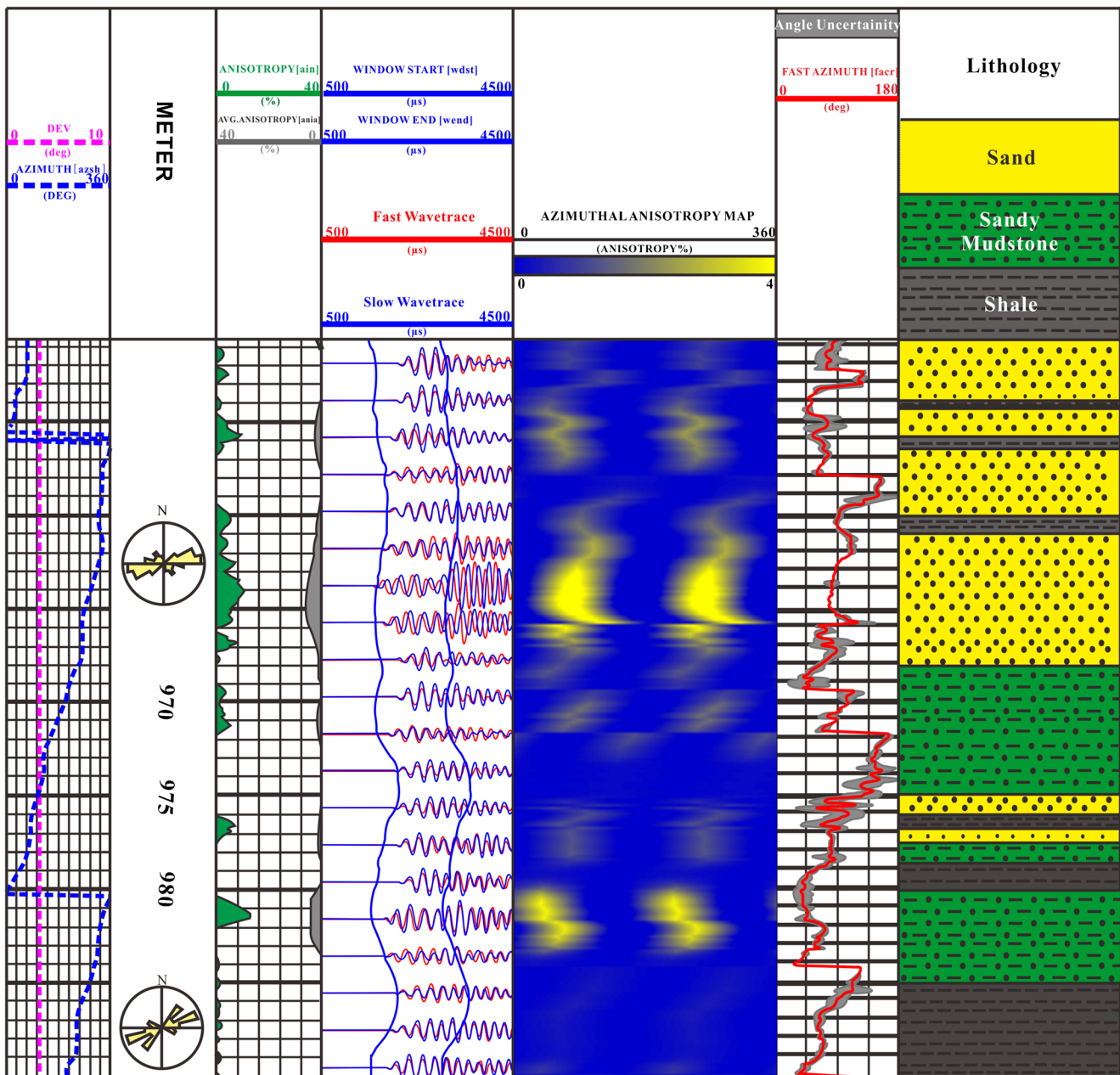
Fig. 7 Results of anisotropy analyses of well B7 (950–990 m): (first column) angle of instrument measurements and well derivation; (second column) anisotropic rose diagram of the strata (statistical frequency: 25 m), where yellow reflects the degree of anisotropy; (third column) anisotropic percentage of the strata (ANI) and average anisotropic percentage of the strata (ANIA); (column 4) selected time window, including the shapes of slow shear waves (SWV) and fast shear waves (FWV); (column 5) azimuthal anisotropic image of fast waves and slow waves; (column 6) azimuth of fast shear waves (FACR) and the uncertainty of the azimuth of fast shear waves; (column 7) lithology of the target strata

Well B7 is on the 2D surveying line with approximately NW–SE direction (Fig. 1). Tectonic interpretations were made from the impedance data of the 2D surveying line (Fig. 5), which was inversed from the seismic data. There is a normal fault (FD108, labeled (1)) on the 2D surveying line, which extends upward to the shallow strata, runs downward through the entire coal measure strata, and reaches the deep Carboniferous and Ordovician strata. Hence, the strata from Neogene to Ordovician are all disturbed and truncated. Influenced by this major fault, a series of secondary normal faults have been produced. Therefore, it was inferred that if the faults are not filled with carbonaceous or argillaceous cements, phreatic water and karst

water in Carboniferous limestone and Ordovician limestone will enter the target seams through the faults.

Stratigraphic and paleogeomorphic reconstructions were performed in accordance with the framework of the tectonic evolution of the study area (Fig. 6), and the influences of tectonic stresses in different periods on the formation of fractures were determined. After flatting of the Quaternary and Neogene strata, coal seams 13-1 and 11-2 (Fig. 6a, b, and c), faults (1)–(3) all remained. After the construction of coal seam 8 (Fig. 6d), fault (3) (FD108-1) gradually disappeared, indicating that it developed after the sedimentation of coal seam 8. Finally, after the construction of coal seam 6 (Fig. 6e), faults (1)–(3) exhibited little change, while after the reconstruction of coal seam 1 (Fig. 6f), all faults disappeared.

Based on the reconstructed stratigraphic profile, the sedimentary evolution during different geological periods could be deduced. Subjected to the influence of a relatively intense stretching stress, fault (1) (FD108) developed during the deposition of Quaternary strata, and the fault wall intersected the entire Quaternary and coal measure strata. By virtue of the cascading effects of this tectonic movement, faults (2), (3), and (4) were produced. After a long geological period, the coal measure strata experienced left-to-right strike-slip movements (e.g., Fig. 5), resulting in the bending of the wall of fault (4).

It can be inferred that fault (1) gradually formed after the sedimentation of coal measure strata and during the deposition of Quaternary strata, and it caused the formation of faults (2), (3), and (4). The stratum truncated by fault (2) is exactly where the target segment rests, and it has a NE–SW stretching stress (stress F1) on the target segment. Later, a NW–SE stress direction caused the entire section to undergo strike-slip movements, which exerted a NW–SE stress (F2) on the target segment. The exertion of stresses on the target segment caused the formation of fractures. Under the impact of stress F1, NW–SE fractures may have developed near fault (1). Later, under the impact of stress F2, the direction of the fractures may have gradually turned toward the NE–SW. The existence of these fractures could lead phreatic water and karst water to migrate into the coal measure strata.

Fracture development

As shown in Fig. 7, the degree of anisotropy of the target strata at well B7 were calculated through the analysis of shear wave splitting. The angle of instrument measurement (0° in the vertical direction), ranging from 0 to 360° is shown in Fig. 7, and the measurements spiral from shallow to deep strata. The well derivation was always 3°. The statistical frequency shown by the anisotropic rose diagram of the strata was 25 m, and indicated that anisotropy was strong in the E–W and NE–SW directions. The anisotropic percentage of the strata (ANI) and the average anisotropic percentage of the strata (ANIA)

were used to intuitively show the anisotropy of the strata. Using the shapes of slow shear waves (SWV) and fast shear waves (FWV), we found that they did not match well with each other, especially in some depth segments. Through the integration of the anisotropic data and neotectonic movement, the anisotropy and fracture distribution of the target well section was determined as follows:

1. The distributions of the ANI and ANIA revealed that the anisotropy of the strata is distributed between 951–957 m, 959–972 m, 976–977 m, and 980–982 m.
2. Within the selected time window (500–4500 μs), the energy and amplitudes of fast and slow shear waves become substantially stronger with the passage of time, and areas with large phase differences revealed that their corresponding stratigraphic positions (950–958 m, 960–968 m, and 980–983 m) exhibited higher degrees of anisotropy.
3. The trend of the azimuth of the fast shear wave (FACR) seen in Fig. 7 was parallel to the trend shown in the anisotropic azimuth. This conforms to the theory that the direction of fast shear waves is the direction of stratigraphic anisotropy.
4. In line with the analysis of neotectonic movement, fault (2) imposes a NE–SW stretching stress (F1) on the target segment, while strike-slip movements exert a NW–SE stress (F2). Taking the results of the acoustic dipole logging into consideration, we found that the anisotropic rose diagrams of the strata obtained at an interval of 25 m represented the anisotropic azimuths of segments at depths of 950–975 m and 975–1000 m. The directions of fracture development are NEE–SWW and NE–SE, respectively, which are approximately orthogonal to the direction of the NW–SE stress (F2) in the tectonic evolution of the study area.

Therefore, the fractures in the target well section (sand–mudstone) between coal seam 1 and coal seam 6 are developed to a great extent. They will provide conduits and space for the seepage and accumulation of groundwater and stimulate water inrush.

Conclusions

The production dynamic data of the Huainan Mining Group show that the largest aquifer in the Huainan Coalfield mainly consists of phreatic water in the shallow sections of Cenozoic and Quaternary strata (< 120 m), confined water, and karst water in Carboniferous and Ordovician limestones. The faults in the coal measure strata within the study area penetrate all of the strata from the Neogene to Carboniferous, causing the

groundwater to enter the strata. The fractures produced by tectonic stress around faults have become the seepage conduits of groundwater, and allow the water to enter coal seams and their roofs and floors. Thus far, water inrush has been found in the exploited upper coal seams, indicating the existence of water-conducting fractures in the surrounding rocks of these seams. The verification of the approximate locations of tectonic fractures through acoustic dipole logging is reliable. Using this method, we found that there are fractures in the target segment of well B7, and thus groundwater is quite likely to accumulate in this fracture zone.

If the under-group coal seams are to be exploited, groundwater will likely burst into the target seams, especially coal seam 1, which is more than 1000 m deep and the closest to the karst aquifer. Therefore, the phreatic water and the nearest confined karst water will increase the difficulty and threaten the safety of coal production. To avoid water inrush into the mine, preventative measures should be given priority and combined with mine management. In the practical operation of the mine, real-time monitoring should be conducted. The topography of the area to be mined should be studied and inspected before mining and a comprehensive management with proper methods and technologies should be implemented.

The major focus of this study was the coal mine water hazards caused by faults and its resulting fractures. To prevent such disasters as water inrush, water-conducting faults may be plugged, horizontal wells may be drilled to discharge underground water, or fracturing technologies may be used to discharge underground water and CBM. The analysis of tectonic evolution and fine-scale detection of fractures, as performed in this study, are useful for determining the conduits of groundwater, and therefore aid in the prediction of potential water hazards in coal mines to ensure the safety of coal mine operations.

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