Water Conductivity Evaluation of Fault F22 Based on Comprehensive Analysis of Multisource Information

Jing Han, Fang Wang, Daolei Xie,* Huide Zhang, Zhaolong Hou, and Xinghong Jiang

ABSTRACT: Mine water disasters are one of the main disasters threatening safe mine operations. If a fault becomes a water guide channel, it often causes serious water inrush accidents in mining. Therefore, accurate evaluation of fault hydraulic conductivity is very important for the prediction and prevention of mine water disasters. To prevent and control mine water disasters and ensure safe mining of coal seams in the presence of faults, this paper takes the F22 fault in the Jinqiao Coal Mine as an example; proposes three highly applicable fault water conductivity evaluation methods based on analysis of water−rock stress, difference analysis of hydrochemical characteristics, and difference analysis of water pressures for the same aquifer on both sides of the fault; and comprehensively analyzes and evaluates the water conductivity of the F22 fault. The results are as follows: the cross-sectional pressure of the fault is greater than the aquifer water pressure and the plastic deformation strength of mudstone combined. The hydrochemical characteristics of the three-ash aquifers on both sides of the fault are obviously different. The water in the three-ash aquifer on one side of the fault has been drained for a long time, while the water pressure on the other side of the fault has not changed significantly. Based on a comprehensive analysis, it is judged that the F22 fault is not water-conducting. The evaluation results are consistent with geophysical explorations and the actual mine roadway exposure, which verifies the feasibility and rationality of the fault water conductivity evaluation method described above.

1. INTRODUCTION

Coal is the main energy source in China, has a wide range of uses, and has been irreplaceable for a long time.1 With the continuous expansion of mining scale and mining depth, the fracture properties of coal and rock masses, distribution characteristics of stress fields, dynamic response characteristics, and disaster-causing mechanisms of deep mines are becoming increasingly complex, especially under the influence of deep and large fault structures, and disasters such as gas outbursts, water inrushes, and rock bursts are prone to occur.2 China produces large amounts of coal with many coalfield geological types and extremely complex structures, and the causes of mine water disasters are extremely diverse; among these, mine water inrush caused by fault water conduction plays a leading role in mine water disasters. Faults are the main form of geological structure in mining areas and are affected by complex hydrogeological conditions, which make their water content and conductivity differ in the direction or region; this makes the surrounding aquifers heterogeneous, anisotropic, and more likely to cause water disasters.3−5 There are many traction fissures and fracture zones near some very large faults, which not only lead to water permeability, water conductivity, and rapid filling from channels but also cause the channels to develop into water-containing bodies that can become water-filling sources because of their own water-containing space.6

Once these faults become water channels located between coal seams and aquifers, they pose a serious threat to the normal and safe operation of coal enterprises.7 Therefore, it is of great practical significance to determine the hydraulic conductivities of faults and then devise rational mine water control projects.6,9 In addition, it is found through research and investigation that the reservoir discontinuous boundary is an important geological factor that blocks oil−water flow. The obvious differences in lithology, physical properties, and permeability between sand bodies caused by fault structures have a great impact on reservoir connectivity.10−13 The research methods in this paper are also applicable to the research of natural gas hydrate exploration. Therefore, the research method of fault water conductivity in this paper has reference significance for the prediction and characterization of reservoir discontinuous boundary.

Received: July 20, 2022
Accepted: September 28, 2022
Published: October 11, 2022
In recent years, many scholars have used lithologic analysis, geophysical exploration, hydrogeological drilling, pumping, drainage and communication experiments, and hydrochemical analysis to judge the hydraulic conductivities of faults. Among them, geophysical prospecting, pumping and discharging tests, and hydrochemical analysis methods are widely used in mine hydrogeology research. The mine seismic reflection wave method was combined with instantaneous electromagnetic technology to explore the fault zone position and water-rich properties of a mining area in detail; controlled source audio-frequency magnetotellurics, referred to as CSAMT, can better reflect the water conductivities of hidden structures in deeply buried strata and the water richness of coal seam roofs and floors; Li realized high-precision advanced detection based on the type of water-bearing abnormal body and comprehensive mine geophysical exploration technology combining earthquake and electromagnetic methods; underground water-conducting structures and their groundwater runoff modes were analyzed accurately by observing the natural electromagnetic field; whether there was a hydraulic connection between vertical and lateral faults was judged by pumping and discharging experiments and connecting experiments. Zhang used a water release test and analyses of hydrochemical characteristics to study the water conductivity of a deep mine boundary fault. The smear coefficient analysis method was used to quantitatively study fault sealing and performed SGR classification to judge fault water conductivity. Chen used principal component analysis of multivariate statistics to determine ion sources and temporal and spatial distributions of aquifers controlled by faults and karst collapse columns. By comparing the hydrochemical characteristics and environmental isotopes present on both sides of a fault, it was concluded that two aquifers were connected. Yang and Man used the similarities and differences in hydrochemical characteristics of different aquifers in a Piper three-line diagram to identify the water inrush source and the water seepage on both sides of the fault, which provided a basis for prevention and control of karst water disasters.

Since they are affected by the complicated geological structures of mining areas, all methods have certain limitations. Although there are many kinds of geophysical prospecting methods, each has its advantages and disadvantages, which are easy to be limited when applied to complex hydrogeological environments. Drilling usually measures representative strata at a single point. This method can only probe local sections of large faults but cannot establish the water conductivities of faults comprehensively. Therefore, it is unreasonable to simply determine whether a fault conducts water according to measurement results. Using comprehensive analyses of fault cross-sectional pressure, aquifer hydrochemical characteristics, water pressure, and other factors, this paper presents three highly applicable methods for the evaluation of fault water conductivity based on analyses of water—rock stress, differences in hydrochemical characteristics, and differences in water pressure for the same aquifer on both sides of a fault; comprehensively analyzes and evaluates the water conductivity of the F22 fault; and verifies these results by actually determining whether the fault gushes water.

2. DESCRIPTION OF THE STUDY REGION

2.1. Geological Survey of the Mining Field. The Jinqiao Coal Mine is located in southwestern Jining City, Shandong
Province. The geographical location is 116°13′57″ E–116°22′30″ E longitude and 35°04′08″ N–35°08′45″ N latitude and covers an area of approximately 39.40 km². The designed production capacity was 600,000 t/a, and the approved production capacity in 2009 was 810,000 t/a. Stratigraphic regionalization in the Jinqiao Mine belongs to the Jining Stratigraphic Community in the Luxi Stratigraphic Subdivision of the North China Stratigraphic Area. The strata developed under the Quaternary are Neogene, Paleogene, Jurassic, Permian, and Carboniferous from top to bottom. At present, the No. 3 coal seam is mainly mined, and the mining methods are the longwall retreating mining method, fully mechanized top-coal caving technology, and full caving method to manage the roof. The coal seam as a whole presents a monoclinal top-coal caving technology, and full caving method to manage the roof. The coal seam located at the bottom of the syncline is thick, and its wings are relatively thin, with an average thickness of approximately 6.5 m.

The Jinqiao Coal Mine is located in the middle of the Chengwu-Zaozhuang Sag in the east-west direction, which is a wide and gentle fold with an axial direction close to east-west. Affected by the compressive stress in the north-south direction and the later tectonic movement, it is characterized by the alternation of wide and gentle folds and faults with high angles, large drops, and long extensions. Faults are mainly distributed near the boundary of the No. 4 mining area, and most of them are high-angle normal faults lying near the SN direction. The F22 fault, the research object of this paper, is located on the northwest boundary of northern mining area No. 4 (Figure 1). It is a normal fault with a fault distance of 50–170 m, trending NE and NW, with an inclination angle of approximately 65 and an extension length of 668 m in the area.

2.2. Hydrogeological Conditions. The mine field is located in the flat Yellow River Plain, where thick loose strata are deposited. The fourth mining area is obviously affected by large faults, and three sides receive groundwater recharge, which places it in the regional hydrogeological unit. The northern boundary is affected by the fault zone, and the roof and floor of the coal seam are basically covered with Ordovician limestone, which forms the boundary of the Ordovician limestone supply. The eastern part is the F7 fault dense zone, and the underground drilling exploration of F7 fault water is preliminarily judged as the Ordovician limestone recharge boundary. The outcrop area in the south is a weak replenishment boundary, and only the F22 fault in the west is basically impermeable to water and forms a water-resisting boundary. The main surface water system is composed of the new Wan Fu River, which flows through the mine field from west to east, with a maximum flow of 742 m³/s.

The aquifers in the mining area from top to bottom are the Cenozoic gravel pore aquifer group, bedrock weathered fissure aquifer, Shaxi Group 3 coal roof sandstone fissure aquifer, Taiyuan Group 3 lime and Shixia lime karst fissure aquifer, and Middle Ordovician limestone karst fissure aquifer. Among them, coal roof No. 3, floor sandstone, and ash No. 3 are direct water-filled aquifers for mining coal No. 3; coal No. 16 and coal No. 17 are direct water-filled aquifers; and the rest are indirect water-filled aquifers. There are three water-resisting layers in the mining area, namely, the water-resisting layer of lower group II of the Cenozoic, the stone box group, and the water-resisting layer group from the floors of the No. 16 coal and No. 17 coal to the Ordovician limestone roof. According to analyses of sandstone thickness and structural complexity, the northeastern North No. 4 and South No. 4 mining areas are rich in water, the southwestern part has limited water, and the remaining areas, including the F22 fault, have medium water contents. Underground water-filling channels are mainly mining fractures, fault fracture zones, closed poor boreholes, and karst collapse columns. Coal No. 3 has been mainly mined since it was put into production, and the water gushing from coal No. 3 is sandstone water on the roof and lime water on the floor.

3. ANALYSIS AND EVALUATION OF FAULT WATER CONDUCTIVITY

Exploration data and actual underground exposure data show that the faults in the mine field are affected by development characteristics such as fault mechanical properties, lithology of upper and lower walls, and fault scale, which makes the water content and water conductivity different in different sections. Affected by changes in hydrogeological conditions in various areas, the lithologic docking relationship and stress state distribution of the same fault are different in different areas, so the water content and conductivity of the same fault in different directions and different parts may change; that is, local water conduction and local water resistance or a fault exposed for the first time will lead to delayed water conduction during mining disturbances. Therefore, to avoid the omission of water-conducting points caused by the targeted exploration of fault water-conducting properties in special sections, this paper comprehensively evaluates the water-conducting properties of faults from three perspectives: water-rock stress analysis, difference analysis of hydrochemical characteristics between the two sides of the fault, and difference analysis of water pressures on both sides of the fault. See Figure 2 for the schematic diagram of influencing factors of fault water conductivity.

![Figure 2. Schematic diagram of influencing factors of fault water conductivity.](https://doi.org/10.1021/acsomega.2c04597)

3.1. Evaluation of Fault Water Conductivity Based on Water–Rock Stress Analysis. Because faults cut through different aquifers on the profile, the water-rich and water-conducting properties of faults are often related to the lithologies of both sides of faults. When the mined coal seam is docked with the opposite aquifer, the fault will easily become a mine water inrush channel and cause water inrush. There are many bedrock aquifers in the geological profile of the same mining area, some of which are disconnected because the
vertical fault distance is greater than the thickness of aquifers or form relatively independent blocks due to the discontinuity of sand body distribution, and their vertical and lateral hydraulic connections with upper and lower aquifers are affected by the surrounding water–rock stress relationship. Therefore, evaluating fault hydraulic conductivity based on water–rock stress analysis is the key to understanding the hydraulic connection between bedrock aquifers and taking effective measures to prevent and control water flow. In view of the close relationship between hydraulic conductivity and the sealing properties of faults, the latter can be evaluated by the normal pressure of the fault plane, and then, information on the hydraulic conductivities of faults can be obtained. By comparing the cross-sectional pressure of the fault with the critical value of mudstone plastic deformation, we can judge whether the fault fissure will be blocked by mudstone, and by comparing the cross-sectional pressure of the fault with the water pressure, we can judge whether the fault plane is likely to open under the action of water pressure. We will evaluate the water conductivities of faults from these two perspectives.

3.1.1. Plastic Deformation Analysis of Mudstone. It is one of the key factors that affect the hydraulic conductivity of faults whether the mud components in the fault zone can flow and plug the fractures after plastic deformation. Whether plastic deformation of mudstone components can occur depends on the comparison between the calculated value of normal pressure and the plastic deformation strength of mudstone. It is known that the critical value of plastic deformation of mudstone is 5 MPa. When the normal pressure of the cross section reaches or exceeds 5 MPa, the mudstone in the fault zone will flow after undergoing plastic deformation at this pressure. The fault fracture zone will be filled with mud, exhibiting low permeability, and the joint surface will be smeared with mudstone to form a more continuous water-blocking boundary that is not conducive to infiltration and migration of groundwater near the fault. At this time, the water conductivity of the fault is weak.

3.1.2. Analyses of Water–Rock Stress. Faults can be effective barriers to fluid flow. Whether the fractured aquifer uses the fracture zone as a water channel also depends on the relationship between the water pressure and the normal pressure of the cross section. When the water pressure is greater than the normal pressure of the section, the fracture surface is opened by the water pressure, and the fault shows good water conductivity at this time. When the cross-sectional pressure is greater than the water pressure, the water pressure is unable to open the fracture surface, and the water conductivity of the fault is poor.

3.1.3. Comprehensive Standard for Evaluation of Fault Water Conductivity. Along with the plastic deformation of mudstone and the water–rock stress, the hydraulic conductivities of faults can be comprehensively analyzed and evaluated. When the normal pressure of the cross section is less than the water pressure and less than the plastic deformation strength of mudstone, the fault hydraulic conductivity is defined as good. When the cross-sectional pressure is less than one of the factors, the hydraulic conductivity is defined as the medium. When the cross-sectional pressure is greater than both the water pressure and the plastic deformation strength of mudstone, the fault hydraulic conductivity is defined as poor.

Aquifers greatly affected by the F22 fault are the floor three-ash aquifer and the Ordovician limestone aquifer. Whether the fault conducts water from these two aquifers has a great influence on safe mine production. The above two criteria are used to evaluate the water conductivity of fault F22 in the three-ash aquifer and Ordovician limestone aquifer. The specific methods are shown below. The equation for calculating the normal pressure of the cross section is

$$P = Z(\rho_f - \rho_w)\cos \alpha + \sigma \sin \alpha \sin \beta$$

where $P$ is the normal pressure of the cross section, $Z$ is the buried depth of the fault plane, $\rho_f$ is the average density of overlying strata, $\rho_w$ is the formation water density, $\sigma$ is the regional principal compressive stress, $\alpha$ is the dip angle of the fault plane, and $\beta$ is the included angle between $\sigma$ and the fault strike.

$Z$ is determined by taking the buried depth of the third coal floor near the fault. According to rock physical and mechanical test data for the Jinqiao Coal Mine, $\rho_f$ takes the maximum value of the test as 0.0027 kg/cm$^3$. The value of $\rho_w$ is 0.001 kg/cm$^3$. According to the results of in situ stress test results for the Jinqiao Coal Mine, this is taken as 15.54 MPa, and the azimuth angle is 74.8. According to the ground stress test results for the Jinqiao Coal Mine, $\sigma$ is taken as 15.54 MPa. The dip angle $\alpha$ of the fault plane is $70^\circ$, and the included angle $\beta$ between $\sigma$ and the fault strike is $52^\circ$. According to the above equation, the normal pressure of the F22 fault section is 11.17 MPa.

3.1.3.1. Head Pressure Calculation. According to the observation data for water stored in the hydrogeological observation hole, the initial water level of $-50.906$ m recorded in hole No. 4–1 for the three-ash aquifer and the normal maximum water level of $-41.67$ m recorded in hole No. 4–3 for the Ordovician limestone aquifer in the last 3 years were used to calculate the water pressure on the coal seam near the fault. According to the calculation, the head pressure of the three-ash aquifer is 5.29 MPa and that of the Ordovician limestone aquifer is 5.39 MPa.

By comparison, the normal cross-sectional pressure of fault F22 is greater than the plastic strength of mudstone (5 MPa) and is greater than the head pressure of the three-ash aquifer and Ordovician limestone aquifer. Based on the comprehensive evaluation of fault water conductivity, it is judged that the water conductivity of fault F22 is poor at these two key aquifers.

3.2. Evaluation of Fault Water Conductivity Based on the Analysis of Hydrochemical Characteristics. By comparing the hydrochemical types and special chemical components present on both sides of the fault zone, the similarities and differences between them can be used to judge whether the fault is likely to conduct water. If the fault zone conducts water, there are basically no differences or only normal differences in the hydrochemical characteristics of the aquifers on both sides of the fault. However, if the hydrochemical characteristics on opposite sides are obviously different and abnormal, the fault is not considered to be conducting water. The hydrochemical characteristics of samples taken from the three-ash aquifers on both sides of fault F22 in the area were analyzed, and the water conductivity of the fault was evaluated according to the differences in hydrochemical characteristics between the two plates. In this paper, the hydrochemical test data of the three-ash aquifer in the second mining area, the fifth mining area, and the drainage point in the last 10 years were counted. Among them, the three-ash hydrogeological observation well in the second and fifth mining areas is located in the footwall of the F22 fault, and the hydrophobic point is also located in the footwall of the F22.
fault (Figure 1). According to the characteristic ions of mine water, the test items of samples are anions, cations, and salinity. The contents of cations detected are those for $K^+$, $Na^+$, $Ca^{2+}$, and $Mg^{2+}$, and the contents of anions detection are those for $Cl^-$, $SO_{4}^{2-}$, and $HCO_3^-$. In the following, the chemical components of lime water on both sides of the F22 fault are presented by drawing rose diagrams and Piper three-line diagrams (Figures 3–8) for the water samples.

### Table 1. Hydrochemical Characteristics Analysis of Three-Ash Water Samples in the Second Mining Area and the Fifth Mining Area at Different Times

| Items analyzed (mg/L) | Cation | Anion | Mineralization degree |
|-----------------------|--------|-------|-----------------------|
|                       | $K^+$  | $Na^+$| $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $SO_{4}^{2-}$ | $HCO_3^-$ |                        |
| 2013.08.03 mining 2#  | 361.78 | 8.94  | 3.22      | 62.13      | 290.69 | 401.63       | 1220.72    | 1220.72 |
| mining 5#             | 461.64 | 72.77 | 35.62      | 124.68     | 931.23 | 309.94       | 1956.47    | 1956.47 |
| 2014.04.25 mining 2#  | 329.06 | 8.15  | 5.44      | 63.34      | 314.57 | 289          | 1101.07    | 1101.07 |
| mining 5#             | 396.42 | 16.3  | 19.78     | 100.26     | 542.2  | 307.39       | 1429.3     | 1429.3  |
| 2015.04.29 mining 2#  | 368.37 | 8.2   | 3.73      | 55.2       | 270.19 | 350.38       | 1145.05    | 1145.05 |
| mining 5#             | 288.99 | 8.2   | 3.73      | 55.2       | 132.64 | 368.5        | 932.1      | 932.1   |
| 2015.10.26 mining 2#  | 394.24 | 13.18 | 7.99      | 67.92      | 347.56 | 581.49       | 1434.14    | 1434.14 |
| mining 5#             | 363.5  | 25.05 | 8.79      | 85.39      | 384.42 | 318.22       | 1240.67    | 1240.67 |
| 2016.04.20 mining 2#  | 422.89 | 11.27 | 9.57      | 62.46      | 356.5  | 587.88       | 1474.49    | 1474.49 |
| mining 5#             | 326.65 | 13.52 | 10.93     | 79.18      | 259.27 | 357.84       | 1122.51    | 1122.51 |
| 2016.11.03 mining 2#  | 428.78 | 16.6  | 5.03      | 61.96      | 356.07 | 589.38       | 1482.44    | 1482.44 |
| mining 5#             | 393.49 | 12.45 | 5.03      | 65.45      | 347.12 | 602.48       | 1449.07    | 1449.07 |
| 2017.07.06 mining 2#  | 357.12 | 9.12  | 6.15      | 57.75      | 324.06 | 552.31       | 1333.72    | 1333.72 |
the second and fifth mining areas, long-range drilling holes were constructed for hydrogeological exploration in the two mining areas, and water samples were not taken regularly for hydrochemical characteristics analysis. Table 1 contains the hydrochemical test data of the three-ash aquifer in different periods in the second and fifth mining areas located in the upper wall of the F22 fault. The ion contents and salinities of the two areas were quite different in the early stage of testing.

Figure 4. Piper trilinear diagrams of three-ash water samples from the observation well in the second mining area at different times.

Figure 5. Piper trilinear diagrams of three-ash water samples from the observation well in the fifth mining area at different times.
and the ion contents and salinities gradually approached each other in the later stage, which indicates that there is a hydraulic connection between the three-ash aquifers in the second and fifth mining areas, and they are in the same hydrogeological

Table 2. Hydrochemical Characteristics Analysis of Three-Ash Drainage Points

| sample point position | cation (mg/L) | | | anion (mg/L) | | | mineralization degree |
|----------------------|---------------|---|---|---------------|---|---|---|
|                      | K + Na⁺      | Ca²⁺ | Mg²⁺ | Cl⁻          | SO₄²⁻ | HCO₃⁻ |             |
| supplementary borehole 4−1# | 2018.7.26    | 524.43 | 229.22 | 102.55       | 162.41 | 1553.69 | 235.44 | 2819.52   |
|                       | 2018.11.28   | 480.11 | 194.9  | 82.17        | 140.45 | 1501.98 | 209.88 | 2632.61   |
|                       | 2019.01.03   | 474.53 | 284.32 | 103.65       | 140.23 | 1670.03 | 188.89 | 2885.22   |
|                       | 2019.01.17   | 443.75 | 270.6  | 95.26        | 134.25 | 1606.56 | 181.02 | 2754.89   |
| crossdrift in eastern tunnel X2# | 2019.05.13   | 444.65 | 306.81 | 106.11       | 167.92 | 1806.22 | 196.76 | 3055.15   |
|                       | 2019.09.09   | 486.19 | 367.75 | 119.76       | 183.36 | 2067.3  | 195.19 | 3442.75   |
|                       | 2020.02.24   | 481.09 | 390.14 | 121.34       | 183.79 | 2164.6  | 222.38 | 3610.97   |
| original No. 3 contact tunnel 1# | 2018.11.28   | 480.11 | 194.9  | 82.17        | 140.45 | 1501.98 | 209.88 | 2632.61   |
|                       | 2019.01.03   | 474.53 | 284.32 | 103.65       | 140.23 | 1670.03 | 188.89 | 2885.22   |
|                       | 2019.01.17   | 443.75 | 270.6  | 95.26        | 134.25 | 1606.56 | 181.02 | 2754.89   |
|                       | 2019.05.13   | 444.65 | 306.81 | 106.11       | 167.92 | 1806.22 | 196.76 | 3055.15   |
|                       | 2019.09.09   | 486.19 | 367.75 | 119.76       | 183.36 | 2067.3  | 195.19 | 3442.75   |
|                       | 2020.02.24   | 481.09 | 390.14 | 121.34       | 183.79 | 2164.6  | 222.38 | 3610.97   |

Figure 6. Rose diagrams of three-ash water samples taken from the drainage points at different times. (a) 4−1# 2018/7/26, (b) X2# 2018/11/28, (c) X2# 2019/1/3, (d) X2# 2019/1/17, (e) 1# 2019.5/13, (f) 1# 2019.9/9, and (g) 1# 2020/2/4.
unit. Three groups of data obtained recently were selected to draw the rose diagram for water samples in the second mining area and the fifth mining area (Figure 3), which shows the dominant ion components present in the three-ash water samples in different periods. The rose diagram of water samples in the second mining area is almost the same concave.
polygon cross-sectional pressure, and the shape changes little. Combined with the characteristics of the ion concentration distribution in the three-line diagram (Figure 4), the hydrochemical characteristics of the three-ash aquifer in the second mining area have changed little in recent years. The rose diagrams of water samples in different periods of the fifth mining area are also an approximate concave polygon. The content changes in \( \text{SO}_4^{2-} \) and \( \text{HCO}_3^- \) anions make the rose diagrams and the three-line diagram (Figure 5) in different periods show some differences, and the content of other ions is generally consistent, which indicates that the hydrochemical characteristics of the three-ash aquifer in the No. 5 mining area have changed little in recent years.

### 3.2.2. Hydrochemical Characteristics of the Three-Ash Aquifer in the Footwall of the Fault.

Three-ash water samples from the footwall of the fault were taken from two drainage points and hole No. 4–1. The water samples of hole No. 4–1 showed the hydrochemical characteristics before drainage, and the other water samples at drainage points are from the initial stages of drainage to the present. Table 2 shows that before the water was drained (July 26, 2018) and at the initial stage (November 28, 2018), the cations in water were mainly \( \text{Na}^+ \), followed by \( \text{Ca}^{2+} \), and the anions were mainly \( \text{SO}_4^{2-} \), followed by \( \text{HCO}_3^- \). With the work of draining water, the salinity and contents of some ions, such as \( \text{Ca}^{2+}, \text{SO}_4^{2-}, \text{and Cl}^- \), increased, but the types of dominant ions remain unchanged. In Figure 6, the sampling points were similar in shape, and the content of dominant ions was unchanged. In Figure 7, the distribution of ions in water samples was relatively concentrated in the Piper three-line diagram. Therefore, overall, the hydrochemical characteristics of this area in the footwall of the F22 fault did not change obviously with time.

### 3.2.3. Comparison of Hydrochemical Characteristics of the Three-Ash Aquifer on Two Sides of F22 Fault.

The hydrochemical test data shown above for each aquifer block indicate that the salinities of water samples from the second and fifth mining areas located in the footwall of the F22 fault were medium, with an average value of approximately 1300 mg/L (Table 1), while the salinities of water samples for the footwall of the fault were as high as approximately 3000 mg/L (Table 2). On the one hand, groundwater with high salinity is often relatively independent, which indicates that the F22 fault serves as a water-resisting boundary; this makes the hydrogeological environment of the footwall relatively stable and imparts high salinity. On the other hand, the differences in mineralization degrees for the three-ash water samples on both sides of the fault reflect the poor fluidity of the aquifers on both sides and suggest that there are no obvious hydraulic connection. Therefore, the F22 fault exhibits poor water conductivity.

It can be seen from the rose diagrams and Piper trilinear diagrams (Figure 8) for water samples in the second mining area, the fifth mining area, and the drainage point that the water qualities of the second and the fifth mining areas are similar, but that of the three-ash in the drainage point is completely different. It can be concluded that the second and fifth mining areas located in the upper wall of the fault belong to the same hydrogeological unit, while the drainage point located in the lower wall of the fault belongs to another hydrogeological unit. The reason for this is that fault F22 divides the three-ash aquifer in this area into two independent blocks (Figure 1), which makes the hydrogeological units on both sides of the fault show obvious hydrochemical character-

### 3.3. Evaluation of Fault Water Conductivity Based on the Observation and Analysis of Hydraulic Pressure.

The hydraulic gradient around the fault zone is strongly controlled by hydrogeological processes such as groundwater extraction or recharge. While continuously draining the water outlet on one side of the fault, the water pressure change in the same aquifer is monitored in the hydrological observation well on the other side of the fault. This method can be used to judge whether the fault conducts water. If the water pressure decreases, the aquifers on both sides of the fault are conductive and have a certain hydraulic connection; that is, the fault conducts water. If the water pressure basically does not change, it means that the butting surface between the upper and lower walls of the fault forms a water-blocking boundary, and the fault does not conduct water.

**Figure 1** shows that there are two drainage points in the footwall of the F22 fault in the mining field that drain the three-ash water, and the three-ash observation well in the second mining area located in the footwall of the fault is used to monitor the water pressure. The first drainage point is located in the three-ash drainage hole of the third winding roadway in the original east wing; drainage started on December 30, 2018, with an initial water inflow of approximately 2 m³/h and a maximum water inflow of 130 m³/h. The second drainage point is located in the three-ash drainage hole of the Shimen No. 1 drilling chamber in the east wing track, where water discharge began on November 28, 2018, with an initial water inflow of 1.54 m³/h and a maximum water inflow of 170 m³/h. According to analyses of hydrochemical characteristics, the water sources for the two water discharge holes are the three-ash water in the footwall of fault F22 branch 2. To date, the water pressure in the three-ash observation well of the second mining area has remained at approximately 3.8 MPa, and no significant change has occurred. This shows that due to the blocking action of the F22 fault, the drainage point in the footwall of the fault does not have a significant influence on the three-ash aquifer in the upper wall of the fault, so the fault does not conduct water.

### 4. RESULTS AND DISCUSSION

This paper proposes three evaluation methods to judge whether large faults in minefields conduct water. The first method is based on the normal pressure of the fault plane. On the one hand, it analyzes whether the normal stress of the fault plane can cause the plastic rheology of mudstone and smear it on the fault plane to prevent water flow. On the other hand, it judges whether the water pressure on the top of the aquifer through which the fault passes is greater than the normal pressure of the fault plane, in which case water gushes into the fault zone. The second method involves analyses of water samples from both sides of a fault in the same aquifer and judges whether the fault conducts water according to the differences in hydrochemical characteristics between the two plates. The third method involves draining water in the aquifer on one side of the fault, dynamically monitoring the water pressure of the same aquifer on the other side of the fault, and analyzing whether there is a hydraulic connection between the two sides of the fault according to whether the water pressure changes obviously. The three methods of analysis are different, and there is no obvious correlation. Comprehensive analysis can ensure the accuracy of the evaluation results.
In this paper, the water conductivity of the F22 fault in the Jinqiao Coal Mine was comprehensively evaluated using the above method and multisource information, and the results showed that the fault does not conduct water. In the actual mining process, the F22 fault was exposed at working faces such as the belt downhill in the east wing and Shimen in the east wing track, and no water outlet was found by monitoring, which verified that the comprehensive evaluation of fault water conductivity with the above three methods was accurate.

5. CONCLUSIONS

The normal pressure of fault F22 is greater than the plastic deformation strength of mudstone and the water pressure of each aquifer, so the fault plane has no opening trend and mudstone can smear the fault plane under the action of force. By comparing the hydrological observation wells of mining areas No.2 and No. 5 on the upper wall of the fault with the three-ash water samples from the drainage point on the lower wall, it can be seen that the water qualities on opposite sides of the F22 fault are quite different, and there is no obvious hydraulic connection. The water pressure in the upper wall of the three-ash observation wells was monitored while draining water from the upper wall of the fault. The water pressure is basically stable and exhibits no obvious change, which indicates that the F22 serves effectively as a barrier and that the hydraulic connection between the two walls of the fault is poor. The above methods all show that the hydraulic connection between the two sides of the F22 fault is poor and that there are no water conduction conditions, so it is comprehensively established that the F22 fault does not conduct water.

Water-rock stress analysis, hydrochemical characteristics analysis, and water pressure monitoring are methods for evaluating fault water conductivity, which comprehensively consider multisource information, such as fault section pressure, hydrochemical characteristics of aquifer water, and water pressure. The analysis factors are comprehensive, and the results are accurate and reliable. These methods overcome the limitation of single-point drilling exploration and also avoid the disadvantage that geophysical exploration is easily interfered, so that these methods can be integrated to evaluate the water conductivity of faults with a certain scale. The evaluation method is not limited by the hydrogeological conditions of the mining area and has universal applicability. Therefore, the water conductivity evaluation of faults with a certain scale in each mining area can be carried out.

AUTHOR INFORMATION

Corresponding Author

Daolei Xie — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China; orcid.org/0000-0002-5363-095X; Email: skd994469@sdust.edu.cn

Authors

Jing Han — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China
Fang Wang — Jinqiao Coal Mine in Jining City, Jining 272000, China
Huide Zhang — Shandong Lineng Luxi Minging Co., Ltd., Jining 272000, China
Zhaolong Hou — Shandong Xinkuang Zhaoguan Energy Co., Ltd., Dezhou 253000, China

Xinghong Jiang — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acsomega.2c04597

Author Contributions

J.H.: methodology, formal analysis, and writing—original draft; F.W.: validation and investigation; D.X.: project administration, funding acquisition, and writing—review and editing; H.Z.: data curation; Z.H.: visualization; and X.J.: software and resources.

Funding

This research was financially supported by the National Natural Science Foundation of China (Grant No. 41702305) and the National Key Research and Development Program of the 13th Five-Year Plan (2017YFC0804100). The authors are extremely grateful for the financial support from these organizations.

Notes

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

REFERENCES

(1) Wei, J. C.; Xiao, L. L.; Niu, C.; Yin, H. Y.; Shi, L. Q.; Han, J.; Duan, F. T. Characteristics analysis of the correlation factors of China mine water hazard accidents in 2001-2013. China Sciencepap. 2015, 10, 336–341.
(2) Tang, Y. Z. Technical problem and countermeasures to deep coal mining in Huainan Mining Area. Coal Sci. Technol. 2017, 45, 19–24.
(3) Shi, S. Q.; Wei, J. C.; Xie, D. L.; Yin, H. Y.; Li, L. Y. Prediction analysis model for groundwater potential based on set pair analysis of a confined aquifer overlying a mining area. Arab. J. Geosci. 2019, 12, 115.
(4) Tan, F.; Cheng, X. Z.; Xie, D. L.; Man, X. Q.; Wei, J. C.; Xu, J. G.; Han, J.; Zhang, G. X. Water abundance prediction of sandstone aquifers based on the distance function. Arab. J. Geosci. 2021, 14, No. 849.
(5) Wei, J. C.; Niu, H. G.; Xie, D. L.; Yin, H. Y.; Li, G. H.; Zhong, C. W.; Li, L. N.; Xu, Y. Y. Water permeability evaluation of fault zone in underground coal mines. Arab. J. Geosci. 2021, 14, 525.
(6) Lu, T.; Liu, S. D.; Wang, B. Application of integrated mining geophysical method in detection of water-bearing faults. Prog. Geophys. 2015, 30, 1371–1375.
(7) Du, M. Z.; Zhang, Y. C.; Li, L.; Mou, Y.; Wang, G. K. Application of CSAMT in the detection of water conductivity in deep buried concealed faults. Coal Eng. 2020, 52, 92–96.
(8) Han, C. H.; Xu, J. G.; Zhang, W. J.; Wei, J. C.; Yang, F.; Yin, H. Y.; Xie, D. L. Assessment and Grouting of Water Inrush Induced by Shaft-Freezing Holes in the Yingpanhao Coal Mine, Inner Mongolia, China. Mine Water Environ. 2021, 1–14.
(9) Han, C. H.; Wei, J. C.; Zhang, W. J.; Zhou, W. W.; Yin, H. Y.; Xie, D. L.; Yang, F.; Li, X.; Man, X. Q. Numerical Investigation of Grout Diffusion Accounting for the Dynamic Pressure Boundary Condition and Spatiotemporal Variation in Slurry Viscosity. Int. J. Geomech. 2021, 21, No. 04021018.
(10) Liu, W.; Hu, L.; Liao, Y.; Wang, L. L.; Jia, S. G.; Wu, W. Z. Identification of undercut channel in deep water central Canyon of South China Sea and its influence on reservoir heterogeneity. Pet. Geol. Eng. 2022, 36, 54–61.
(11) Zou, M.; Xia, D. L.; Xia, D. D.; Pang, W. A Study on the Cause of Tight Sandstone Reservoir Heterogeneity. J. Southwest Pet. Univ. 2022, 44, 41–52.
(12) Fan, T. E.; Wang, H. F.; Hu, G. Y.; Song, L. M. Fluvial Reservoir Discontinuous Boundary and Its Influence on Oilfield Development. *China Offshore Oil Gas* **2021**, *33*, 96–105.

(13) Ren, J. J.; Liu, X. H.; Niu, M. Y.; Yin, Z. Y. Effect of sodium montmorillonite clay on the kinetics of CH₄ hydrate-implication for energy recovery. *Chem. Eng. J.* **2022**, *437*, 2026–2036.

(14) Li, W.; Mou, Y.; Qiu, H. Application of Mine Comprehensive Geophysical Detection Methods on Water Bearing Abnormal Bodies. *Saf. Coal Mines* **2017**, *48*, 208–211.

(15) Wang, L. Y. The natural electric field dynamic characters of fracture water in fault. *Coal Geol. Explor.* **2012**, *40*, 76–78.

(16) Bian, K.; Xu, J. P.; Gui, H. Study on Water Conductivity of Magmatic Intrusion Fault in Bucun Mine. *Min. Saf. Environ. Prot.* **2010**, *37*, 44–46+50.

(17) Cui, F. P.; Wu, Q.; Liu, S. Q.; Ji, Y.; Wang, W. J. Testing and Analysis of the Water Conductivity of the North-South Boundary Fault in Huozhou Ganhe Mine Field. *Min. Saf. Environ. Prot.* **2019**, *46*, 98–102.

(18) Yang, T. T.; Xu, G. Q.; Yu, S. T.; Su, Y.; Zheng, Z. Y.; Li, Z. H. An analysis of the chemical composition characteristics and formation of the karst groundwater in the Taiyuan Group in the lower part of a coal seam. *Hydrogeol. Eng. Geol.* **2019**, *46*, 100–108.

(19) Zhang, S. J.; Ding, Y. H.; Jiang, C. L. Experimental Research on the Water Transmissibility of Large-scale Boundary Fault in Deep Mine. *Min. Res. Dev.* **2017**, *37*, 11–14.

(20) Zheng, Z. Y.; Xu, G. Q.; Yang, T. T.; Yu, S. T.; Zhang, H. T. Hydrochemical formation mechanism and transmissivity-impermeability analysis of karst groundwater on both sides of fault F104 in Gubei coal mine in Huainan. *Coal Geol. Explor.* **2020**, *48*, 129–137.

(21) Zhang, W. Q.; Li, W.; Zhang, G. P.; Zhang, G. B. Water Controlling Research of Complex Fault Structures in Wugou Mine. *Adv. Mater. Res.* **2012**, *616−618*, 499.

(22) Chen, H. J.; Li, X. B.; Liu, A. H. Studies of water source determination method of mine water inrush based on Bayes’ multi-group stepwise discriminant analysis theory. *Rock Soil Mech.* **2009**, *30*, 3655–3659.

(23) Chen, L. W.; Liu, X.; Yin, X. X.; Gui, H. R. Analysis of hydrochemical environment evolution in main discharge aquifers undermining disturbance in the coal mine. *J. China Coal Soc.* **2012**, *37*, 362–367.

(24) Man, X. Q.; Wei, J. C.; Xie, D. L.; Xie, C. L. Identification method of water inrush source based on analysis of hydrochemical characteristics. *China Sciencepap.* **2021**, *16*, 76–81.

(25) Li, G. H.; Wang, J.; Xie, D. L.; Wei, J. C.; Liu, P. Evaluation of water conductivity based on fault sealing property and design of water-proof coal pillar. *China Min. Mag.* **2021**, *30*, 138–143.

(26) Cilona, A.; Aydin, A.; Johnson, N. M. Permeability of a fault zone crosscutting a sequence of sandstones and shales and its influence on hydraulic head distribution in the Chatsworth formation, California, USA. *Hydrogeol. J.* **2015**, *23*, 405–419.

(27) Wang, W. J. Research on Water Control Effect of Xiatuanbai Fault. *Min. Saf. Environ. Prot.* **2015**, *42*, 72–75.

(28) Faulkner, D. R.; Jackson, C. A. L.; Lunn, R. J.; Schlische, R. W.; Shipton, Z. K.; Wibberley, C. A. J.; Withjack, M. O. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *J. Struct. Geol.* **2010**, *32*, 1557–1575.

(29) Wang, M. Y.; Gao, P.; Cui, H. Q. Study on the method of determining the vertical conductivity of mine fault zone. *J. Liaoning Tech. Univ.* **1995**, *14*, 53–56.

(30) Aydin, A.; Eyal, Y. Anatomy of a normal fault with shale smear: implications for fault seal. *AAPG Bull.* **2002**, *86*, 1367–1381.

(31) Fu, G.; Liu, H. X.; Duan, H. F. Seal Mechanisms of Different Transporting Passways of Fault and Their Research Methods. *Pet. Geol. Exp.* **2005**, *27*, 404–408.

(32) LYU, Y. F.; Wang, W.; Hu, X. L.; Fu, G.; Shi, J. J.; Wang, C.; Liu, Z.; Jiang, W. Quantitative evaluation method of fault lateral sealing. *Pet. Explor. Dev.* **2016**, *43*, 340–347.

(33) Fisher, Q. J.; Haneef, J.; Grattoni, C. A.; Allshorn, S.; Lorinczi, P. Permeability of fault rocks in siliciclastic reservoirs: recent advances. *Mar. Pet. Geol.* **2018**, *91*, 29–42.

(34) Bense, V. F.; Gleeson, T.; Loveless, S. E.; Bour, O.; Scibek, J. Fault zone hydrogeology. *Earth-Sci Rev.* **2013**, *127*, 171–192.