Permeability Loss of Bituminous Coal Induced by Water and Salinity Sensitivities: Implications of Minerals’ Occurrence and Pore Structure Complexity

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1. INTRODUCTION

Coalbed methane (CBM) development is regarded as an effective method for supplying coal-based clean energy and alleviating the greenhouse effect induced by CH₄ discharge during coal mining.¹⁻⁵ In 2020, 5.76 × 10⁹ m³ CBM was produced in China (on the ground surface), and recently, the CBM industry in northwestern China has developed rapidly. A vertical well located in the southern Junggar Basin⁶ yielded a peak production of 17,125 (m³/d). A CBM development block named Baiyanghe,⁷ with an annual gas production of 30 Mm³, has been established as the first demonstration base for CBM utilization in the southern Junggar Basin. Although progress has been achieved, the production of a significant number of CBM wells in northwestern China was lower than 500 m³/d, which need to be urgently improved for better economic performance.

Reservoir damage can impede fluid flow during oil and gas production, leading to the generation of low-yield wells.⁸,⁹ The contact between minerals and externally invaded fluids can result in decreased seepage capacity and permeability of the coal reservoir.¹⁰ Minerals of the reservoir may be sensitive to water, salt, acid, and alkali.¹¹,¹² Currently, research studies on those sensitivities controlled by mineral migration and pore structure complexities of bituminous coal are insufficient. Low- and high-salinity water is applied in CBM drilling and fracturing processes in northwestern China; hence, the water sensitivity (WS) and salinity sensitivity (SS) of coal reservoirs are to be urgently investigated for instructing the work fluid design there.

Mineral migration, swelling, and aggregation were thought to be the vital factors controlling WS and SS damage degrees. Fang et al. found that the number of small pores increases and that of big pores decreases after WS due to clay migration, leading to porosity reduction and permeability impairment.¹³ Alhuraisha-wy et al. reported that the detachment of clay particles after WS has a significant effect on the permeability reduction of a reservoir.¹⁴ Wang et al., Zhang et al., Tao et al., and Zhao et al. reported that WS mechanisms are hydration and swelling of clay minerals and particle migration.¹⁵,¹⁶,¹⁷ Yang et al. first presented and visualized conclusive evidence for fines migration during the WS process by applying X-ray micro-computed tomography.¹⁸ Zhao et al. reported that the main mechanisms of SS are that fines can easily detach, migrate, and finally plug the...
pore throats under a salt environment.\textsuperscript{19} Zhang et al. presented that the change in the water film thickness, the enhancement of hydrophilia, the particle detachment, and the dissolution of quartz or albite contribute to WS damage under high-temperature conditions.\textsuperscript{20} Wang et al. implemented that pH can control the change in the thickness of the water film during SS, leading to seepage space variation.\textsuperscript{21}

The aforementioned recent research progress on WS and SS could be briefly summarized as that the detaching, expanding, dispersing, migrating, and depositing of minerals induced the permeability loss. However, three deficiencies still exist: (1) minerals’ migration pathways during WS and SS are still unclear; (2) the pore structure can control the reservoir damage degree;\textsuperscript{22} however, it is unclear whether minerals’ plugging or pore structure complexity plays a dominating role in determining the WS or SS damage degree; and (3) WS and SS of bituminous coals deposited in northwestern China are scarcely investigated.

To address the aforementioned issues, the following content, aimed at revealing the implications of mineral migration and pore structure complexity on WS and SS of bituminous coals deposited in northwestern China, was analyzed: (1) medium-volatile bituminous coal (MVBC) and high-volatile bituminous coal (HVBC) of northwestern China were sampled; (2) mineral composition and occurrence characteristics were detected by the TESCAN Integrated Mineral Analyzer (TIMA) and scanning electron microscope as well as energy dispersive spectrometer (EDS); (3) WS and SS were simulated using HVBC and MVBC specimens, and low-field nuclear magnetic resonance (LFNMR) tests before and after WS and SS were conducted; (4) the relationship between the transverse relaxation time ($T_2$) and pore diameter was determined, and then, space variations of pores on different scales and minerals’ migration pathways were discussed; (5) pore-throat structures were analyzed by rate-controlled mercury penetration (CMP), and the influences of the pore structure on WS and SS were revealed; and (6) WS of different ranked coals was discussed by combing predecessors’ published work. The results of this study can enhance the scientific understanding on the WS and SS of coal and provide instructions on CBM development in northwestern China.

2. GEOLOGICAL BACKGROUND

HVBC is accumulated in the Mesozoic coal measures in the southern Junggar Basin, northwestern China, where samples for this study were collected. The southern Junggar Basin, with a length of 500 km and a width of 40–90 km,\textsuperscript{23} is characterized by multi-depositional and multi-typed structural systems including reverse faults and a series of anticlines as well as synclines.\textsuperscript{24} The multi-depositional and multi-typed structural systems including Jurassic Xishanyao Formation (J2x) are the main coal-bearing strata. The J1b mainly consists of glutenite, siltstone, silty mudstones, and coal seams. The J1b mainly consists of glutenite, siltstone, silty mudstones, and coal seams. The J1b mainly consists of glutenite, siltstone, silty mudstones, and coal seams. The J2x primarily consists of conglomerates, sandstone, siltstone, black mudstones, and coal seams. The J2x primarily consists of conglomerates, sandstone, siltstone, black mudstones, and coal seams. CBM resources are 6.21 × 10$^{15}$ m$^3$ in the Turpan-Hami Basin.\textsuperscript{25} To date, the CBM development in the Turpan-Hami Basin is at an early stage of exploration.

3. METHODS

A pore-size distribution classification scheme proposed by Cai et al.,\textsuperscript{34} stating that micro-pores, transition pores, meso-pores, macro-pores, and super macro-pores are 2–10, 10–100, 100–1000, 1000–10,000, and >10,000 nm in diameter, respectively, was applied in this research. Figure 1 depicts the research workflow of this study: (1) the mineral composition and occurrence state were analyzed by TIMA and SEM, respectively, as well as EDS technologies; (2) the pore-size distribution was determined by combining corrected mercury intrusion porosimetry (MIP) data and low-temperature nitrogen adsorption (LTNA) data, and the relationship between the transverse relaxation time ($T_2$) and pore diameter was determined by comparing the pore-size distribution and $T_2$ spectrum obtained by the LFNMR test; (3) If WS and SS simulations as well as LFNMR tests before and after those simulations were conducted, then volume variations of pores with different diameters could be analyzed by transferring $T_2$ to the diameter; and (4) influences of mineral migrations and pore structure complexity on WS and SS were discussed.

3.1. Sample Collection and Treatment. Coal blocks (30 cm × 30 cm × 30 cm, approximately) were sampled from the Wudong coal mine and Kuangou coal mine located in the southern Junggar Basin as well as the Ewirgol coal mine located in the northwestern Turpan-Hami Basin, northwestern China. The mean maximum vitrinite reflectance, proximate analysis, and coal composition tests were conducted according to the standards of ISO 7404-5:2009, ISO 17246-2010, and ISO 7404-3:2009, respectively (Table 1). According to the American Society of Testing Materials Standard ASTM D388-2015, samples from the Wudong coal mine and Kuangou coal mine are...
Table 1. Results of Proximate Analysis and Coal Composition of Coal Samples

| sampling sites | coal type   | macroscopic coal petrography | $R_{\text{max}}$ (%) | proximate analysis (%) | coal composition (%) |
|----------------|-------------|-----------------------------|----------------------|------------------------|----------------------|
| Wudong         | HVBC        | semi-bright coal            | 0.72                 | 2.53                   | 32.24                 |
| Kuangou        | HVBC        | semi-bright coal            | 0.73                 | 3.66                   | 36.73                 |
| Ewirgol        | MVBC        | semi-bright coal            | 1.26                 | 3.66                   | 30.27                 |

$\text{Abbreviations: HVBC = high-volatile bituminous coal; MVBC = medium-volatile bituminous coal; } R_{\text{max}} \text{ = maximum reflectance of vitrinite, } \% ; \ A_d = \text{ash content on a dried basis, } \% ; \ V_{\text{d,ad}} = \text{volatile matters yield on dry and ash-free basis, } \% ; \ V = \text{vitrinite content, } \% ; \ I = \text{inertinite content, } \% ; \text{ and } E = \text{exinite content, } \% .$

Table 2. Allocation of Coal Samples for Different Tests

| targeted experiments | specifications                        |
|----------------------|--------------------------------------|
| MIP                  | cylindrical cores 10 mm in height and 25 mm in diameter |
| LTNA                 | 60–80 meshed powder coal samples     |
| LFNMR                | cylindrical cores 25 mm in diameter and 30 mm in length |
| WS/SS simulations    | cylindrical cores 45 mm in height and 25 mm in diameter |
| TIMA                 | flat plate specimens 5–25 mm in length and 5 mm in thickness |
| SEM and EDS          | small blocks with 10 mm × 10 mm × 3 mm in dimension |
| CMP                  | cylindrical coal cores 10 mm in height and 25 mm in diameter |

$\text{Abbreviations: MIP = mercury intrusion porosimetry; LTNA = low-temperature nitrogen adsorption; LFNMR = low-field nuclear magnetic resonance; WS = water sensitivity; SS = salinity sensitivity; CMP = rate-controlled mercury penetration; SEM = scanning electron microscope; and EDS = energy dispersive spectrometer.}$

HVBC, named as HVBC1 and HVBC2, respectively. Samples from the Ewirgol coal mine are MVBC, and these samples are named as MVBC1. Samples were treated into seven types from the same coal blocks, which were used for MIP, LTNA, LFNMR, WS and SS simulations, TIMA, SEM and EDS, and CMP, respectively. Details on these types of samples were introduced in Table 2. It should be noted that, to weaken the influences of heterogeneity, samples used for MIP, LFNMR, WS and SS simulations, and CMP were obtained by cutting the same long cylindrical sample drilled along the direction parallel to the bedding plane from the coal block.

3.2. TIMA, SEM, and EDS. Mineral composition and distribution were characterized by TIMA, which can combine the back-scattered electron and energy-dispersive X-ray in conjunction with advanced image and pattern recognition analysis. In this study, samples were analyzed in the high vacuum mode using modal analysis under an accelerating voltage setting of 25 kV, a working distance setting of 15 mm, and a field size setting of 1500 μm. SEM and EDS tests were applied, and the samples were polished by argon ion polishing using the Hitachi IM4000 argon polishing device. SEM maps were observed, and EDS detections were conducted using a double-beam electron microscope system named FEI Helios 650.

3.3. WS and SS Evaluation. WS simulations using cylindrical cores were conducted according to the following steps: (1) samples were first vacuumed for 24 h after drying at 110 °C for 24 h, then they were saturated with formation water at 1 MPa for 24 h. The saturation time of 24 h was applied because the $T_2$ signal of LF-NMR no longer increased after 10 h since the beginning of the saturating process; (2) initial permeability ($k_i$) was measured by injecting formation water into the sample under a flow rate setting of 0.05 mL/min, which was far less than the critical velocity sensitivity flowing rates (2 mL/min) tested ourselves and 0.9–1.2 mL/min referenced by Tao et al. of bituminous coals deposited in northwestern China. The confine pressure was set to 10 MPa for the purpose of simulating the in situ coal reservoir condition using an experimental setup displayed in Figure 2; (3) after step (2), the experimental samples were subjected to the LFNMR test for the purpose of obtaining the $T_2$ spectrum before WS; (4) work fluid with 75% formation water salinity (FWS) was injected into the core at a flow rate of 0.05 mL/min under the confine pressure of 10 MPa, then permeability was measured after the inlet pressure and the outlet pressure were steady; (5) permeability of the cylindrical cores during the injection of work fluids with 50% FWS, 25% FWS, and distilled water were measured subsequently; and (6) after step (5), the cylindrical cores were subjected to LFNMR again for the purpose of obtaining the $T_2$ spectrum after WS to distinguish the pore space variation before and after WS simulation. Before conducting the whole experimental procedures, LFNMR of the same standard sample was tested three times and the $T_2$ spectra of those three were the same, thus the instrument error of LFNMR can be eliminated.

Work fluids with 100% FWS, 200% FWS, 400% FWS, and 800% FWS were used in SS simulations. Other procedures of SS
were similar to those of WS as introduced above. Permeability can be calculated according to Darcy’s law

\[ k = \frac{Q \mu L}{A \Delta P} \times 10^{-2} \]  

(1)

where, \( k \) is the fluid permeability, mD; \( Q \) is the flow rate, cm³/s; \( \mu \) is the fluid viscosity, mPa·s; \( L \) is the core length, cm; \( A \) is the cross-sectional area of the core, cm²; and \( \Delta P \) is the differential pressure on both ends of the coal sample, MPa.

Permeability damage ratios of WS and SS were calculated by eq. 2

\[ \text{permeability damage ratio} = \left( \frac{k_{fw} - k_i}{k_f} \right) \times 100\% \]  

(2)

where, \( k_{fw} \) is the fluid permeability for each kind of work fluid and mD; \( k_i \) is the fluid permeability under 100% FWS conditions, mD.

3.4. Pore-Size Distribution Characterization. MIP tests were conducted by using an AutoPore IV 9500 mercury injection apparatus. The maximum mercury injection pressure, mercury surface tension, and contact angle were 100 MPa, 485 in·cm, and 130°, respectively. A significant compression in the coal matrix can be observed as the mercury intrusion pressure increases during MIP measurements, leading to the generation of an inaccurate pore-size distribution result. An effective MIP data correction method proposed and applied by Han et al., Shao et al., and Zhang et al. was applied in this study, whose details can be referred to in Appendix A. An automatic specific surface and pore analyzer, Tristar II 3020, was applied for LTNA tests. After high-temperature drying and degassing processes, samples were applied for LTNA tests at 77.3 K with relative pressures ranging from 0.001 to 0.995. The pore-size distribution of the coal sample in this research was obtained by combining data results from the MIP test and LTNA test, whose details can be referred to in Appendix A.

3.5. Determination of the Relationship between the \( T_2 \) Value and Pore Diameter. There is a consistent one-to-one match between the relaxation time (\( T_2 \)) value and pore diameter, namely the greater the \( T_2 \), the greater the corresponding pore diameter. In this study, \( T_2 \) spectra were detected using an LFNMR device named RecCore-2500. Additionally, the relationship between the \( T_2 \) value and pore diameter was quantitatively determined by comparing the accumulated pore volume of pore-size distribution with an accumulated signal value of the \( T_2 \) spectrum. The determination process of the relationship between \( T_2 \) and the pore diameter can be referred to in Appendix B, and then the \( T_2 \) spectrum can be regarded as a direct pore-size distribution after transferring the \( T_2 \) value to the pore diameter.

3.6. CMP. CMP can distinguish pores and throats and calculate the pore-throat quantity ratio with extremely low-speed mercury intrusion. A CMP device named APSE730 was used for the measurements. Samples were first dried for 24 h at the temperature of 120 °C, then mercury was injected into the samples with an extremely low speed of 0.00005 mL/min. The maximum injection pressure was 6.2057 MPa. The contact angle and surface tension between coal and mercury were 130° and 485 in·cm, respectively. The uniformity coefficient of the throat (2σ), throat sorting coefficient (RCth), and averaged pore-throat ratio (Rf-pt), which are parameters reflecting pore-throat structural complexities, can be calculated according to the following equations, namely

\[ a = \left( \sum r_{pt} \right)/r_{max} \]  

(3)

\[ RC_{th} = \sqrt{\sum (r_i - R_{av-th})^2 a_i} \]  

(4)

\[ R_{av-th} = \sum R f_i \]  

(5)

where, \( a_i \) is the distribution frequency of the normalized radius of a throat; \( r_i \) is the diameter of the throat, nm; \( r_{max} \) is the maximum throat diameter, nm; \( R_{av-th} \) is the average throat diameter value, nm; \( R_i \) is the pore-throat ratio; and \( b_i \) is the distribution frequency of the normalized pore-throat ratio.

Table 3. Mineral Compositions of HVBC1 and HVBC2 as well as MVBC1 Samples

| Phase                  | HVBC1 | HVBC2 | MVBC1 |
|------------------------|-------|-------|-------|
| organic component      | 99.52 | 97.91 | 87.12 |
| mineral content        | 0.48  | 2.09  | 12.88 |
| kaolinite              | 0.27  | 0.90  | 8.60  |
| calcite                | 0.01  | n     | 1.79  |
| smectite               | 0.08  | 0.01  | 0.91  |
| apatite                | n     | 0.95  | 0.01  |
| ankerite               | 0.03  | n     | 0.79  |
| pyrite                 | 0.05  | n     | 0.46  |
| gibbsite               | 0.01  | 0.08  | 0.01  |
| albite                 | 0.02  | n     | 0.08  |
| goceixite              | n     | 0.11  | n     |
| Mg_Ca sulphate         | n     | n     | 0.10  |
| quartz                 | n     | n     | 0.07  |
| iron oxides            | 0.03  | n     | 0.01  |
| siderite               | n     | 0.01  | n     |
| other minerals         | 0.01  | n     | 0.05  |

4. RESULTS

4.1. Mineral Compositions. Table 3 and Figure 3 demonstrate each mineral’s content percentage occupying the total coal and total mineral, respectively, detected by TIMA technology. Mineral contents of the two HVBC samples, namely HVBC1 and HVBC2, were merely 0.48 and 2.09% occupying the total coal, respectively, significantly lower than those of the MVBC1 sample (12.88%, Table 3). Kaolinite, pyrite, and smectite take up 56.3, 16.7, and 10.4% of the total mineral content of the HVBC1 sample, respectively (Figure 3a). Calcite, ankerite, goceixite, and albite could also be detected in the HVBC1 sample, although their contents were very low. The mineral content of the HVBC2 sample was mainly dominated by apatite and kaolinite, with a percentage of 45.4 and 43.1%, respectively, compared with those of smectite, ankerite, pyrite, and calcite relatively lower, compared with those of apatite and kaolinite. As for the MVBC1 sample, content percentages of kaolinite and calcite were relatively greater, which were 66.7 and 13.9%, respectively, compared with those of smectite, ankerite, pyrite, albite, and quartz (Figure 3c).
punctuated state (Figure 4a, b) and fractures are not filled by minerals, showing that these minerals are distributed sparsely. As for MVBC1, which is a MVBC sample, minerals are distributed both in fractures and pores, and in addition, the fracture filling degree of MVBC1 is significantly severer than that of HVBC1 or HVBC2 (Figure 4c). It can be found that the kaolinite filling in the pores of MVBC1 is distributed as banded zonation, and almost all fractures of MVBC1 are filled by calcite (Figure 4c).

A kaolinite particle with an irregular hexagon shape (4 μm in side length, approximately), located on the bedding surface rather than pores, is found in spot 1 of Figure 5a. Spot 2 and spot 3 in Figure 5b depict pores filled by apatite and kaolinite, respectively, and both the former and latter minerals are irregular. Figure 5c, d demonstrates pores filled by albite and quartz, showing that the contact between albite (or quartz) and the pore-wall surface is tighter than the contact between kaolinite and the bedding surface in Figure 5a.

Kaolinites with irregular shapes displayed in Figure 6a are very fragile, and their aggregates are cluster-like and stacked on the bedding surface. Spot 2 and spot 3 in Figure 6b depict pores filled by irregular apatite, and it can be seen that the contact between apatite and the pore-wall surface is tight. Figure 6c shows pores filled by dimple-shaped irregular kaolinite. Spot 7 and spot 8 of Figure 6d display irregular quartz and kaolinite particles located in the margins of pore surfaces.

A direction-aligned kaolinite with a strip structure is found in Figure 7a. Figure 7b displays coal pores filled by kaolinite particles. Spot 3 and spot 4 as well as spot 5 in Figure 7c show quartz, kaolinite, and pyrite distributed on the bedding surface. Particles of kaolinite and quartz are found to be attached on the throat wall surface, namely spot 6 and spot 7 in Figure 7d, respectively.

### 4.3. WS and SS Results

For the HVBC1 sample, the permeability tested under work fluid with 75% FWS was obviously lower than that tested under 100% FWS conditions (Figure 8a). As salinity decreased from 75% FWS to 25% FWS, permeability slightly fluctuated. As salinity decreased from 25% FWS to deionized water, permeability decreased sharply. Correspondingly, permeability damage ratio values were stable as salinity decreased from 100% FWS to 25% FWS, and they doubled as salinity decreased from 25% FWS to deionized water. The final WS permeability damage ratio of the HVBC1 sample was 35.5%, falling into the category of medium WS based on the China oil & gas industry standard (SYT5358-2010) (Table 4). The permeability of the HVBC2 sample decreased continually, and the permeability damage ratio of HVBC2 increased continually, as salinity decreased from 100% FWS to deionized water (Figure 8b). The final WS permeability damage ratio of the HVBC2 sample was 23.4%, falling into the category of weak WS. The permeability of the MVBC1 sample first decreased sharply and then steadily, and the permeability damage ratio of MVBC1 increased steadily as salinity decreased from 100% FWS to deionized water (Figure 8c). The final WS permeability damage ratio of the MVBC1 sample was 28.2%, falling into the category of weak WS.

Permeability of the HVBC1 sample decreased continually, but the decreasing degree was slight, and the permeability damage ratio of the HVBC1 sample increased slightly as well, as work fluid salinity increased from 100% FWS to 800% FWS (Figure 8d). The final SS permeability damage ratio of the HVBC1 sample was 10.8%, falling into the category of weak SS. As salinity increased from 100% FWS to 800% FWS, permeability of the HVBC2 sample slightly fluctuated and remained almost unchanged. Correspondingly, the permeability damage ratio values were very small. The final SS permeability damage ratio of the HVBC2 sample was merely 1.7%, falling into the category of no SS (Figure 8e). The permeability of the MVBC1 sample decreased slightly as well, and the permeability damage ratio of the MVBC1 sample increased slightly, as salinity increased from 100% FWS to 800% FWS (Figure 8f). The final SS permeability damage ratio of the MVBC1 sample was 9.8%, falling into the category of weak SS as well. It could be observed from Figure 8 that WS of HVBC and MVBC samples is more obvious than SS of those samples, and samples with a relatively higher WS permeability damage degree also have a relatively higher SS permeability damage degree.

### 5. DISCUSSION

#### 5.1. Pore-Size Distribution Results and the Relationship between $T_2$ and the Pore Diameter

The incremental transition pore volume derived from corrected MIP data was close to that derived from LTNA data because the uncorrected MIP data exaggerated the transition pore volume, as displayed in Figure 9a–c demonstrating the pore-size distribution of the three samples. Compared with using uncorrected MIP data singly, the pore-size distribution combined with corrected MIP data and LTNA data together could be regarded as a more
correct characterization method. The pore-size distribution of the HVBC1 sample was close to that of the HVBC2 sample, manifesting as meso-pore volume or transition pore volume, which was the greatest, followed by macro-pore and super macro-pore volume, and micro-pore volume was the lowest (Figure 9a,b). The pore-size distribution of the MVBC1 sample, which was MVBC, was different from that of the two HVBC samples, demonstrating that macro-pore and super macro-pore volumes were the greatest, followed by meso-pore volume and transition pore volume, and micro-pore volume was the lowest (Figure 9c). The total pore volume of the MVBC1 sample (0.010 cm$^3$/g) was significantly lower than that of HVBC1 and HVBC2 samples, which were 0.040 and 0.042 cm$^3$/g, respectively. Volumes of macro-pores, super macro-pores, meso-pores, and transition pores of the MVBC1 sample were significantly lower than those of the two HVBC samples. The micro-pore volume of MVBC1 was greater than that of the HVBC2 sample but lower than that of the HVBC1 sample, as marked by the red dashed line in Figure 9.

Predecessors did a lot of work on the relationship between the $T_2$ value and pore diameter, using uncorrected MIP data,\textsuperscript{42−44} LTNA data,\textsuperscript{45} or the $T_2$ cutoff method.\textsuperscript{46} LFNMR is an efficient tool for quantifying full-scale pore-size distribution.\textsuperscript{47} The determination of the relationship between $T_2$ and the pore diameter using pore-size distribution of this study can be more accurate, compared with the traditional methods using solo uncorrected MIP data or LTNA data. The quantitative relationships between the $T_2$ value and pore diameter of the three samples, which are revealed according to the calculation method introduced in Appendix B, are demonstrated by each equation in Figure 9d–f, respectively. The cumulative pore volume frequency curves derived from pore-size distributions were close to those derived from LFNMR on the whole, for both of the HVBC and MVBC samples (Figure 9d–f).

![Figure 4. Minerals composition and distribution: (a) HVBC1 sample; (b) HVBC2 sample; and (c) MVBC1 sample.](https://doi.org/10.1021/acs omega.1c05995)
parameters of B-4 were determined by applying the least-square method. Values of $n$ for the three samples were very close, and the value of C for the HVBC2 sample was almost two times and ten times that of the HVBC1 sample and MVBC1 sample.

Figure 5. Minerals’ occurrence states in the HVBC1 sample: (a) kaolinite particle with an irregular hexagon shape located on the bedding surface, noting that the observed layer is the bedding surface; (b) apatite and kaolinite filling in pores; (c) albite filling in pores; and (d) quartz filling in pores.
Figure 6. Minerals’ occurrence states in the HVBC2 sample: (a) kaolinite with an irregular shape is very fragile; (b) irregular apatite filling in pores; (c) dimple-shaped irregular kaolinite filling in pores; and (d) irregular quartz and kaolinite particles.
Figure 7. Minerals’ occurrence states in the MVBC1 sample: (a) direction-aligned kaolinite with a strip structure; (b) kaolinite particles filling in coal pores; (c) quartz, kaolinite, and pyrite distributed on the bedding surface, noting that the observed layer is the bedding surface; and (d) kaolinite and quartz attached on the throat wall surface.
respectively (Figure 9d–f), showing that the relationship between $T_2$ and the pore diameter varies with different samples, even for the two HVBC samples with close maturity (Table 1).

**5.2. Pore Space Variation Before and after WS and SS.**

After determining the relationship between $T_2$ and the pore diameter, volume variations of pores with different diameters can be determined by comparing $T_2$ spectra obtained before and after WS or SS. Figure 10 depicts the diameter-transferred $T_2$ spectra before and after WS or SS. It can be found that, for the HVBC1 sample after WS, volumes of macro-pores (marked by R3) and meso-pores (marked by R2) decreased slightly while those of transition pores (marked by R1) increased slightly (Figure 10a). As for the HVBC2 sample, volumes of macro-pores and super macro-pores (marked by R5) decreased overall, while those of meso-pores (marked by R4) increased slightly (Figure 10b). Moreover, for the MVBC1 sample, volumes of super macro-pores (marked by R9) and meso-pores as well as transition pores (marked by R7) decreased in general, while those of macro-pores (marked by dashed R8) increased dramatically, and those of micro-pores (marked by R6).

![Figure 8](https://pubs.acs.org/journal/acsodf)

Figure 8. Permeability and permeability damage ratio (abbreviated as PDR in this figure) variation as salinity of the experimental fluid decreased [(a) HVBC1 sample; (b) HVBC2 sample; and (c) MVBC1 sample] and increased [(d) HVBC1 sample; (e) HVBC2 sample; and (f) MVBC1 sample].
increased slightly (Figure 10c). For the HVBC1 sample after SS, volumes of macro-pores and super macro-pores (marked by S2 in Figure 10d) decreased slightly, while those of meso-pores (marked by S1) increased slightly (Figure 10d). As for the HVBC2 sample, volumes of macro-pores and super macro-pores (marked by S4) decreased overall, while those of meso-pores and transition pores (marked by S3) increased generally after SS (Figure 10e). As for the MVBC1 sample, volumes of super macro-pores (marked by S9) and meso-pores (marked by S7) as well as micro-pores (marked by S5) decreased, while those of transition pores (marked by S6) and macro-pores (marked by S8) increased (Figure 10f).

5.3. Migration Potential and Migration Pathway of Minerals During WS and SS Processes. For the two HVBC samples, non-clay minerals such as apatite, albite, and quartz are filled in pores, and the contact between those minerals and pore-wall surfaces is tighter than that between clay minerals and bedding surfaces (Figures 5a–d and 6a,b). Additionally, kaolinite particles have poor adhesion to the coal skeleton and weak adhesion between wafers. Therefore, under the action of shear, the kaolinite aggregate falls off from the base of skeleton particles and may also be easily broken into fragments, which can promote its migration. Hence, compared with non-clay minerals, kaolinites in this study are easy to migrate during WS and SS simulation processes. Some quartz and pyrite are found to be distributed on the bedding surface or attached to the throat wall surface in the MVBC1 sample (Figure 7b,d). These quartz and pyrite may migrate during WS and SS simulation processes.

As for clay minerals, only kaolinite and smectite are found in the three samples (Table 3). Kaolinite in the three samples is mainly displayed as particle, attaching on the bedding surface (Figures 5a, 6a, and 7a) or partially filling in meso-pores or transition pores (Figures 6d and 7b,d). Although kaolinite has no swelling ability, it is characterized by easily breaking apart and migrating, then concentrating at the pore-throat, leading to severe plugging and loss of permeability. Hence, those kaolinite particles may result in a permeability decrease during WS and SS simulations. Smectite is 100% expandable, causing loss of porosity and a decrease in permeability, hence a permeability decrease may also be attributed to smectite expanding during WS simulation, particularly for the MVBC1 sample with the smectite content greater than that of the two HVBC samples.

As introduced in Section 5.2, for HVBC samples, transition pore and meso-pore volumes increased overall after WS or SS, while macro-pore or super macro-pore volumes decreased after WS or SS. Combining with that, kaolinite of the two HVBC samples mainly displayed as particles, attaching on the bedding surface or partially filling in meso-pores or transition pores with high potential for detaching and migrating, as introduced in Section 4.2, it can be concluded that a part of kaolinite distributed in meso-pores or transition pores first detached and then migrated to other types of pores during the WS and SS processes, leading to an overall volume increase in transition pores and meso-pores. The migrated kaolinite agglomerated continually during migration and finally deposited in the narrow throat of macro-pores or super macro-pores, leading to a decrease in the macro-pore or super macro-pore volumes and loss of permeability. Figure 11 demonstrates the sketch map of pore-volume variations and kaolinite migration pathways of the two HVBC samples during WS or SS.

As for the MVBC1 sample with high contents of kaolinite and smectite, pore-volume variations after WS or SS were quite complicated, as displayed in Figure 10c,f. Overall, transition pore and meso-pore volumes of the MVBC1 sample decreased after WS, which were different from those variations of the two HVBC samples. It could also be found that the macro-pore volume increased, while the super macro-pore volume decreased for the MVBC1 sample after WS. This phenomenon could be explained as follows: (1) kaolinite was severely filled in macro-pores of the MVBC1 sample, as displayed in Figure 4c, and those kaolinites were detached, migrated, and finally deposited in super macro-pores, leading to a macro-pore volume increase and a super macro-pore volume decrease; and (2) smectite, which was detected by TIMA but not observed by SEM, may have filled in transition pores and meso-pores. The smectites swelled after WS, leading to decreased volumes of transition pores and meso-pores.

The macro-pore volume of the MVBC1 sample increased while the super macro-pore volume decreased as well after SS. This phenomenon could also be explained by the kaolinite filled in macro-pores was detached, migrated, and finally deposited in super macro-pores. Some small coal fines and kaolinite in transition pores may block micro-pores and meso-pores after migration in the SS process of the MVBC1 sample, leading to a volume increase in transition pores and a volume decrease in MP and meso-pores, as displayed in Figure 10f.

Gong reported that SS damage degrees of anthracite samples are weak, which are the same as those of the bituminous coals in this study (Table 5). Because research on the SS of coal is scarce, further discussions are limited. Zhao, Hu et al., Tao et al., Gong, Zuo et al., Tian and Wu applied anthracite samples to study WS; Wang et al. applied lignite samples to study WS; and Gao et al., Geng et al. and we applied bituminous coal samples to study WS. Table 5 displays the results of these studies. It can be seen that WS permeability damage ratios vary tremendously even for coals with the same ranks. For instance, Tao et al. reported WS permeability damage ratios of anthracite, which vary from 5.21 to 52.08, and all data of anthracite from Zhao, Hu et al., Tao et al., Gong, Zuo et al., and Tian and Wu show that WS permeability damage ratios of anthracite vary from 5.21 to 83.06%, indicating that there is no close relationship between the WS damage degree and coal rank.

5.4. Influence of the Pore Structure on WS and SS. Parameters of $R_{\text{Cth}}$ and $R_{\text{WP}}$ were derived by CMP using eqs 3–5. The greater the $a$, the diameters of throats of a sample are closer to the largest throat of the same sample, and the throat diameter is more evenly distributed. The smaller the $R_{\text{Cth}}$, the diameters of throats of a sample are going to be closer to the mean diameter of the same sample and the better the sorting property of the throats of that sample. The greater the $R_{\text{WP}}$, the more complicated the pore-throat structure of the sample. In
summary, the greater the $a$ or the smaller the $R_{Cth}$ or the smaller the $R_{avpt}$, the more homogeneous the structures of macro-pores and super macro-pores of a sample. It could be seen in Table 6 that value $a$ of the HVBC2 sample was the greatest, followed by that of the MVBC1 sample, while that of the HVBC1 sample was the lowest. Values of $R_{Cth}$ and $R_{avpt}$ of the HVBC1 sample were the greatest, followed by those of the MVBC1 sample, and those of the HVBC2 sample were the lowest. These results indicated that macro-pore and super macro-pore structural complexities of the HVBC1 sample were the greatest, followed by those of the MVBC1 sample, and those of HVBC2 samples were the lowest.

As discussed in Section 5.3, the migrated kaolinite was deposited in the narrow throats of macro-pores or super macro-pores, leading to a permeability decrease; thus, structural complexities of super macro-pores and macro-pores may play a key role in determining the WS or SS damage degree. Table 6

![Figure 9. Pore-size distributions (abbreviated as PSD in this figure) derived from the combination of corrected MIP data and LTNA data: (a) HVBC1 sample; (b) HVBC2 sample; and (c) MVBC1 sample; and the cumulative pore-volume frequency curve derived from pore-size distribution data and LFNMR data: (d) HVBC1 sample; (e) HVBC2 sample; and (f) MVBC1 sample. (Abbreviations: MIP = mercury intrusion porosimetry; LTNA = low-temperature nitrogen adsorption; and LFNMR = low-field nuclear magnetic resonance).](https://doi.org/10.1021/acsomega.1c05995)
shows that the WS and SS permeability damage ratios of the HVBC1 sample were the greatest, followed by those of the MVBC1 sample and those of the HVBC2 sample were the lowest. The WS and SS damaged degree orders of the three samples were the same as the macro-pore and super macro-pore structural complexity orders of those three, indicating that WS and SS permeability damage ratios were closely related to structural complexities of macro-pores and super macro-pores. Meanwhile, samples with high clay mineral contents and low values of sum volumes of macro-pores and super macro-pores (taking MVBC1, for instance) were not the severest in WS and SS damage. Therefore, it could be summarized that damage degrees of WS or SS of the three samples were mainly dominated by macro-pore and super macro-pore structural complexities rather than the clay mineral content or pore volume. Hence, the main WS and SS mechanisms of MVBC and HVBC in this study can be summarized as the detachment, migration, and deposition of kaolinite contributing to a macro-pore or super macro-pore volume decrease, and a more complex pore structure with a greater pore-throat ratio and stronger heterogeneity leading to severer plugging of the throat induced by those deposited kaolinites, leading to more permeability loss.

5.5. Influence of Minerals on WS. Tao et al.\textsuperscript{10} and Geng et al.\textsuperscript{58} reported the relationship between WS permeability damage ratios and the mineral content of anthracite and bituminous coal, respectively, and they found that WS permeability damage ratios increase as the mineral content increases, with only two exceptions marked by the blue dashed line in Figure 12a. In

![Figure 10. Pore-volume variation before and after WS simulation: (a) HVBC1 sample; (b) HVBC2 sample; and (c) MVBC1 sample; and pore-volume variation before and after SS simulation: (d) HVBC1 sample; (e) HVBC2 sample; and (f) MVBC1 sample.](https://doi.org/10.1021/acsomega.1c05995)
particular, an obvious increasing trend of the WS permeability damage ratio can be found as the clay mineral content increases, as shown in Figure 12b, which can be evidence that the clay mineral induces the generation of WS. However, as the carbonate mineral content increases, the WS permeability damage ratio generally decreases (Figure 12c). This phenomenon can be attributed to the fact that the contact between the coal matrix and carbonate mineral is so tight that the carbonate mineral is not easily detached from the coal surface. The two exceptions in Figure 12c, marked by the red dashed line, are both high in the carbonate mineral content and clay mineral content, and the latter leads to their high WS permeability damage ratios. The relationship between the WS permeability damage ratio and mineral content of results studied by this paper is not obvious. This is because the WS damage degree of bituminous coal samples of this study is closely related to the pore structure, as discussed in Section 5.4. Figure 12d manifests a negative relationship between the WS permeability damage ratio and 100% FWS permeability; this phenomenon can be attributed to the fact that coal samples with high permeability are usually low in clay mineral content, and these samples are wide in the aperture of the coal fracture. Hence, the detachment, swelling, migration, and deposition of clay minerals have little influence on permeability, and correspondingly, the WS permeability damage ratios of these coals are low. Overall, the clay mineral content, permeability, and pore structure complexity are key factors influencing the WS damage degree.

In the future, the following aspects can be given attention to enhance the scientific understanding of WS and SS, with the purpose of better instructing the actual CBM production: (1) studies on WS and SS must be related to the actual work fluid composition, particularly the conditions of drilling and fracturing as well as workover fluids; (2) comparative studies between coal and different ranks, mineral contents, mineral types, and mineral occurrences using large amounts of samples need to be conducted; and (3) advanced transparent geological analysis technology such as using micro-CT during WS and SS simulations can be conducted to observe the dynamics of reservoirs and minerals during the experimental process.

6. CONCLUSIONS

This work studied and discussed the control of mineral occurrence and pore structural complexity on the WS and SS of bituminous coal deposited in northwestern China; the main conclusions are summarized as follows:

(1) HVBC samples of this study were characterized as medium to weak WS (with the highest permeability damage ratio of 35.5%) and weak SS (with the highest permeability damage ratio of 10.8%) and MVBC samples of this study were characterized as weak WS (with the highest permeability damage ratio of 28.2%) and weak SS (with the highest permeability damage ratio of 9.8%).

(2) Kaolinite, distributed as irregular particles or fragile aggregates attached on the bedding surface or filled in pores, is the dominant clay mineral in HVBC and MVBC of this study. For HVBC samples of this study, the detachment, migration, and deposition of kaolinite contributed to the macro-pore or super macro-pore

| predecessors’ publication | coal type | permeability damage ratios of WS or SS | total mineral content (%) |
|---------------------------|-----------|---------------------------------------|---------------------------|
| Zhao55                    | anthracite| two samples with WS permeability damage ratios of 80.81 and 83.06%, respectively, with an average of 81.93% | 7.50% (clay mineral content) |
| Hu et al.54               | anthracite| one sample with the WS permeability damage ratio of 54.74% | none correlated data published |
| Tao et al.52              | anthracite| Six samples with WS permeability damage ratios of 52.08, 5.21, 6.94, 32.47, 10.59, and 14.14%, respectively, with an average of 20.23% | nine samples with the mineral content of 9.86, 3.50, 11.96, 7.41, 11.63, 2.25, 7.91, 14.89, and 5.70%, respectively, with an average of 8.35% |
| Wang et al.21             | lignite   | one sample with the WS permeability damage ratio of 54.18% | 3.82% |
| Gong22                    | anthracite| four samples with WS permeability damage ratios of 28.71, 43.31, 26.21, and 22.48%, respectively, with an average of 30.18% | none correlated data published |
| Gao et al.57              | bituminous coal | two samples with WS permeability damage ratios of 90.66 and 95.07%, respectively, with an average of 92.87% | none correlated data published |
| Geng et al.58             | bituminous coal | five samples with WS permeability damage ratios of 54.03, 40.26, 47.57, 45.84, and 28.92%, respectively, with an average of 43.53% | five samples with the mineral content of 11.10, 5.70, 8.30, 5.00, and 3.60%, respectively, with an average of 6.74% |
| Zuo et al.55              | anthracite| nine samples with WS permeability damage ratios of 63.63, 52.70, 32.61, 14.23, 14.30, 12.02, 11.13, 7.10, and 5.60%, respectively, with an average of 23.72% | none correlated data published |
| Tian and Wu52             | anthracite| five samples with WS permeability damage ratios of 36.93, 9.91, 32.61, 15.17, and 21.79%, respectively, with an average of 21.05% | none correlated data published |
| Gong25                    | anthracite| four samples with SS permeability damage ratios of 19.39, 18.64, 19.33, 18.64%, respectively, with an average of 18.99% | none correlated data published |
volume decrease after WS or SS. Kaolinites filled in the macro-pores of MVBC of this study detached, migrated, and finally deposited in super macro-pores after WS and SS, leading to losses of super macro-pore volume and permeability;

(3) More complex pore structure with a greater pore-throat ratio and stronger heterogeneity can lead to severer plugging of the throat induced by deposited kaolinite after WS or SS, leading to more permeability loss.

**APPENDIX A**

Coal matrix compressibility can be expressed as (Li et al., 1999)

\[ K_c = \frac{dV_c}{V_c dP} \]  \hspace{1cm} (A-1)

where, \( K_c \) is the coal matrix compressibility, MPa\(^{-1} \); \( V_c \) is the coal matrix volume, cm\(^3\)/g; and \( dV_c/dP \) is the change in the coal matrix volume as the mercury injection pressure changes, cm\(^3\)/ (g·MPa).

For compressible porous coal, the following equation exists during mercury injection (Han et al., 2015)

\[ \Delta V_o = \Delta V_p + \Delta V_c \]  \hspace{1cm} (A-2)

where, \( \Delta V_o \), \( \Delta V_p \) and \( \Delta V_c \) are the injected pore volume, filling pore volume, and compressing matrix volume, respectively, g/cm\(^3\).

A proportional relationship between \( \Delta V_o \) and \( P \) was found for the three samples of this study as \( P \) increased from 35 MPa (corresponding to the pore 51.0 nm in diameter) to 100 MPa (corresponding to the pore 18 nm in diameter), and the proportional constant \( \beta \) can be expressed as

\[ \beta = \frac{\Delta V_o}{\Delta P} \]  \hspace{1cm} (A-3)

Combining eqs A-1—A-3, it can be found that

\[ K_c = \frac{1}{V_c} \left( \beta - \frac{\Delta V_{p1}}{\Delta P} \right) \]  \hspace{1cm} (A-4)

where \( \Delta V_{p1} \) is the volume of pores with a diameter ranging between 18 and 51 nm, which can be obtained from LTNA data.

Assuming that \( K_c \) is constant during mercury injection, the coal matrix volume can be corrected using the following equation (Shao et al., 2018)

\[ \text{Table 6. Values of Macro-Pore Parameters and Permeability Damage Ratios*} \]

| sample     | WS permeability damage ratio (%) | SS permeability damage ratio (%) | \( a \) | RC\(_{th} \) | \( R_{av-pt} \) | sum volume of macro-pores and super macro-pores (cm\(^3\)/g) | kaolinite content (%) | smectite content (%) |
|------------|---------------------------------|---------------------------------|--------|-------------|---------------|-------------------------------------------------|---------------------|---------------------|
| HVBC1      | 35.5                            | 10.8                            | 0.16   | 0.84        | 201.04        | 0.0067                                           | 0.27                | 0.08                |
| HVBC2      | 23.4                            | 1.74                            | 0.51   | 0.45        | 144.08        | 0.0103                                           | 0.90                | 0.01                |
| MVBC1      | 28.2                            | 9.8                             | 0.19   | 0.71        | 214.42        | 0.0038                                           | 8.60                | 0.91                |

* (Abbreviations: WS = water sensitivity; SS = salinity sensitivity; \( a \) = uniformity coefficient of throat; RC\(_{th} \) = throat sorting coefficient; and \( R_{av-pt} \) = average pore-throat ratio).
where $V_{c(p)}$ is the coal matrix volume at a mercury injection pressure of $P_0$, cm$^3$/g and $P_0$ is the initial injection pressure and is equal to 0.0035 MPa.

Then, the actual mercury filling pore volume can be calculated by

$$V_p = V_{c(p)} - K_t V_{c(p)} (P_i - P_0)$$  \hspace{1cm} (A-6)

where $V_{P_i}$ and $V_{c(p)}$ are the actual mercury filling pore volume and actual injected pore volume at a pressure of $P_i$, respectively, cm$^3$/g.

### APPENDIX B

The fluid content and pore structure can be reflected by the proton nuclear magnetic resonance underradio-frequency field. The relaxation characters can be expressed as (Yao et al., 2012)

$$\frac{1}{T_2} \approx \rho_2 \frac{S}{V} = F_r \rho_2 \frac{S}{r}$$  \hspace{1cm} (B-1)

where, $T_2$ represents transverse relaxation time, ms; $S$ represents the pore surface area, μm$^2$; $V$ is the pore volume, μm$^3$; $\rho_2$ denotes the transverse surface relaxativity coefficient, μm/ms; $r$ is the pore radius, μm; and $F_r$ represents the geometry factor. Therefore, there is a consistent one-to-one match between the $T_2$ value and the pore radius.

B-1 can be transferred to B-2 as

$$T_2 = \frac{r}{\rho_2 F_r}$$  \hspace{1cm} (B-2)

In the actual situation, the pores in rocks are quite complex and previous studies (Li et al., 2015; Huang et al., 2018) have found the following relationship between $T_2$ and $r$

$$T_2 = \frac{r^n}{\rho_2 F_r}$$  \hspace{1cm} (B-3)

where $n$ is the power exponent constant. Define $C = 2 \times (\rho_2 F_r)^{1/n}$ and B-3 can be expressed as

$$D \equiv CT_2^{1/n}$$  \hspace{1cm} (B-4)

where $D$ is the pore diameter, μm. In this study, MIP data could reflect the pore-size distribution of pores with a diameter greater than 18 nm, and the incremented pore volume derived from MIP was greater than the actual pore volume due to the compressibility of the coal matrix. Hence, the pore-size distribution of pores with a diameter greater than 18 nm was obtained using corrected MIP data, as illustrated in Appendix A, and the pore-size distribution of pores with the diameter ranging between 2 and 18 nm was derived from LTNA data. Therefore, the combined pore-size distribution derived from corrected MIP data and LTNA data was addressed. The $T_2$ curve derived using a water-saturated specimen can describe the full-scale pore-size distribution of coal. Compared with the volume accumulative curves of $T_2$ and combined pore-size distribution together, the unknown parameters in B-4 can be calculated. Details are as follows:

Take logarithms on both sides of B-4, as follows (Li et al., 2015)

$$\ln r = \ln C + \frac{1}{n} T_2$$  \hspace{1cm} (B-5)

Based on the least-square method, values of $C$ and $n$ can be derived by calculating the minimum value of $L$, which can be expressed as

$$L = \sum_{i=1}^{m} \left[ \frac{1}{n} \ln T_2 + \ln C - \ln r \right]^2$$  \hspace{1cm} (B-6)

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### Notes

The authors declare no competing financial interest.

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(40) Yuan, H. H.; Swanson, B. F. Resolving pore space characteristics by rate-controlled porosimetry. *SPE Form. Eval.* 1989, 4, 17–24.

(41) Toledo, P. G.; Scriven, L. E.; Davis, H. T. Pore-space statistics and capillary pressure curves from volume-controlled. *SPE J.* 1994, 9, 46–54.

(42) Li, A. F.; Ren, X. X.; Wang, G. J.; Wang, Y. Z.; Jiang, K. L. Characterization of pore structure of low permeability reservoirs using a nuclear magnetic resonance method. *J. China Univ. Pet.* 2015, 39, 92–98.

(43) Huang, H.; Sun, W.; Ji, W.; Zhang, R.; Du, K.; Zhang, S.; Ren, D.; Wang, Y.; Chen, L.; Zhang, X. Effects of pore-throat structure on gas permeability in the tight sandstone reservoirs of the Upper Triassic Yanchang formation in the Western Ordos Basin, China. *J. Petrol. Sci. Eng.* 2018, 162, 602–616.

(44) Gong, Y.; Liu, K. Pore throat size distribution and oiliness of tight sands—A case study of the Southern Songliao Basin, China. *J. Petrol. Sci. Eng.* 2020, 184, 106508.

(45) Tang, H. M.; Gong, X. P.; Tang, H. X.; Zhang, L. H.; Zhao, F.; He, Y. Evaluation method and damage mechanism of shale formation sensitivity damage. *J. Cent. S. Univ.* 2016, 47, 1228–1236.

(46) Yao, Y.; Liu, D.; Che, Y.; Tang, D.; Tang, S.; Huang, W. Petrophysical characterization of coals by low-field nuclear magnetic resonance (NMR). *Fuel* 2010, 89, 1371–1380.

(47) Yao, Y.; Liu, D. Comparison of low-field NMR and mercury intrusion porosimetry in characterizing pore size distributions of coals. *Fuel* 2012, 95, 152–158.

(48) Zhao, X. Y.; He, D. B. *Clay Mineral and Application in Oil and Gas Exploration and Development*; Petroleum Industry Press: Beijing, 2016; pp 328–332.

(49) Blume, T.; Weisbrod, N.; Selker, J. S. Permeability changes in layered sediments: impact of particle release. *Ground Water* 2002, 40, 466–474.

(50) Zou, Y. S.; Zhang, S. C.; Zhang, J. Experimental method to simulate coal fines migration and coal fines aggregation prevention in the hydraulic fracture. *Transp. Porous Media* 2014, 101, 17–34.

(51) Civan, F. *Reservoir Formation Damage*; Gulf Professional Publishing: Houston, 2015.

(52) Gong, Z. W. Clay mineral characteristics and sensitivity evaluation of coal reservoirs in Duijiangnan mine field, Guizhou province. *Sci. Technol. Eng.* 2019, 19, 39–45. (in Chinese with English Abstract)

(53) Zhao, Y. H. Reservoir Features and Sensitivity Assessment of a CBM Block in Qinshui Basin, Shanxi. *Coal Geology of China*; Routledge, 2020; Vol. 32, pp 34–38. (in Chinese with English Abstract).

(54) Hu, H. Y.; Zhao, L. Y.; Chen, J.; Yan, Z. H.; Li, Y. K. Influence of coal seam sensitivity on CBM drainage and control strategy in Faer Mining Area. *Coal Sci. Technol.* 2020, 48, 334–340. (in Chinese with English Abstract)

(55) Zuo, Y. Q.; Zhang, X. Y.; Zhou, R.; Li, S. Water sensitivity and its controlling factors on high-rank coal reservoirs in southern Qinshui basin. *Pet. Geol. Recovery Effic.* 2014, 21, 107–110. (in Chinese with English Abstract)

(56) Tian, Y.-D.; Wu, J. Sensitivity of high-rank coal-bed methane reservoir in the Southern Qinshui Basin. *J. China Coal Soc.* 2014, 39, 1835–1839. (in Chinese with English Abstract)

(57) Gao, Z. S.; Yang, B.; Liu, J. S. CBM reservoir damage and reasons of Dafosi well field. *Resour. Ind.* 2018, 20, 47–51. (in Chinese with English Abstract)

(58) Geng, Y. G.; Tang, D. Z.; Xu, H.; Tao, S.; Li, S. Pore cracking features of coal reservoir in Anze Block and water sensitive effect failure mechanism. *Coal Sci. Technol.* 2017, 45, 175–180. (in Chinese with English Abstract)