Hindawi
Geofluids
Volume 2023, Article ID 2455954, 10 pages
https://doi.org/10.1155/2023/2455954

Research Article

A New Mode of Visible Fracture System in Coal Seams and Its Implications for Coalbed Methane Seepage

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Received 13 November 2022; Revised 12 December 2022; Accepted 18 March 2023; Published 11 April 2023

Academic Editor: Yiding Bao

As the central flow channel for fluid seepage through rock layers, the visible fracture system (VFS) significantly affects geoenergy extraction for petroleum, natural gas, geothermal resources, and greenhouse gas sequestration. In this work, we propose a new mode of VFS in coal seams, including hydraulic fractures, exogenetic fractures, interlayer fractures, gas-expanding fractures, and cleats. The development characteristics of VFSs in coal seams are analyzed, including containing their geometry, orientation, scale, distribution, and connection between each other. Furthermore, the implications of the VFS for fluid (gas and water) and solid (coal fines) flow through coal seams are discussed. The development of the VFS determines the effective flow conductivity, affecting the flow of gas, water, and coal fines. Additionally, as the reservoir pressure transfer channel, the VFS significantly influences depressurization with reservoir depletion, determining the extension of the methane desorption range. The exogenetic fractures and interlayer fractures dominate the expansion of the primary hydraulic fractures, and gas-expanding and cleats usually control the branch of hydraulic fractures. Furthermore, we find that the daily production rate distribution of most CBM wells presents a particular banded, L-shaped, or T-shaped pattern. It is thought that the VFS dominates the productivity of CBM in coal seams. The field production data also provide evidence that the occurrence of the VFS makes the CBM reservoir heterogeneous. This study presents a recommended framework involving the characteristics of the VFS and its influences on CBM production.

1. Introduction

Coal seams are typically fractured reservoirs. The fracture system provides the central flow channels for fluid migration through rock layers, affecting geoenergy extraction for petroleum, natural gas, geothermal resources, and greenhouse gas sequestration [1]. More than 80% of coalbed methane (CBM) exists in the coal matrix pores in an adsorption state. By extracting the formation water from coal seams, the fluid pressure decreases to the critical desorption pressure. The adsorbed methane in the coal matrix pores releases and diffuses to the fracture network system and flows to the wellbore [2–4]. The visible fracture system (VFS) in coal seams provides the channels for CBM flow and plays an essential role in CBM production [5]. Therefore, it is of great significance for the efficient extraction of CBM to study the characteristics and implications of the VFS on the CBM seepage [6–8].

Along with the exploration and development of CBM, researchers have intensively studied natural fracture systems in coal seams in the last 30 years. The endogenetic fractures in CBM reservoirs, called cleats, including face cleats and butt cleats, are widely used in coal reservoir evaluation. The two cleats are nearly perpendicular to each other and perpendicular to the stratification of coal seams. Compared to butt cleats, face cleats are more developed and more continuous [9, 10]. The natural fracture system in some coal seams is complicated because of the complex tectonism, various tectonic periods, and intense deformation. Various natural fractures exist in these coal seams [11, 12]. Therefore, the cleats used to describe the natural fracture system in coal seams are limited and cannot accurately represent the occurrence of fractures. Some researchers have investigated and proposed fracture categories based on the geological conditions of China. According to the generation and development characteristics of the fractures, fractures in coal seams can be divided into four levels: large fractures, medium fractures, minor fractures, and microfractures, as shown in Figure 1 [13]. Large and medium fractures are equivalent to exogenetic joints and are the product of the deformation of coal seams. They can develop in any position in coal seams, and the height is several meters. Minor fractures usually intersect with stratification at high angles, extending from several millimeters to several centimeters. Microfractures often develop in vitrain coal and bright coal, and the height is generally several millimeters to several centimeters.

Coal seam fractures can also be divided into horizontal fractures, vertical fractures, and oblique fractures with an angle to the coalbed, depending on the relationship between the exogenetic fractures and the stratification [14]. The inherited fractures are the retransformation of the previously formed cleats, with the mixed properties of cleats and exogenetic fractures, and belong to the transitional type. Wang et al. [15] proposed a mode of VFS based on field investigations in the Ordos Basin and Qinshui Basin, North China. The VFS includes exogenetic fractures, gas-expanding fractures, and cleats. Within the VFS, significant differences in both the geometry and spatial distribution are observed.

The VFS in coal seams controls the permeability of coal seams, which has significant implications for CBM production [8]. For example, the VFS in coal seams plays a substantial role in the design and effect of directional horizontal wells [16, 17]. The developed structural fracture system in coal seams with high connectivity has high permeability, high reservoir pressure transmission efficiency, and high productivity [18]. The heterogeneity of coal seams caused by the VFS controlled by stress is an essential factor affecting the productivity of CBM wells. The development degree and opening of natural fractures maintain heterogeneity in the permeability [19–21]. The development characteristics of macroscopic fractures in coal seams differ in different coal body structures. Although the number and density of fractures in severely broken coal are large, the fracture connectivity becomes extremely poor due to tectonism, which cannot contribute to the production of CBM [22]. Therefore, fracture development is an important reason why tectonically deformed coal cannot contribute to CBM production [23]. Although previous researchers have studied the development characteristics of VFSs with many achievements, they have not yet constructed a geological model of natural VFSs closely related to CBM development [24]. Therefore, it is necessary to closely combine CBM development and VFSs to perform further studies.

The purpose of this work is to investigate the characteristics of a new mode of VFS and its significant implications for CBM production. The VFS is proposed depending on in situ observations in the subsurface coal mines and field tests. The VFS is divided into subclasses, and the development characteristics are analyzed based on the field investigations. Then, the implications of the VFS for CBM production are discussed. This study is aimed at providing necessary theoretical guidance for exploring and developing CBM resources and coal mine gas extraction.

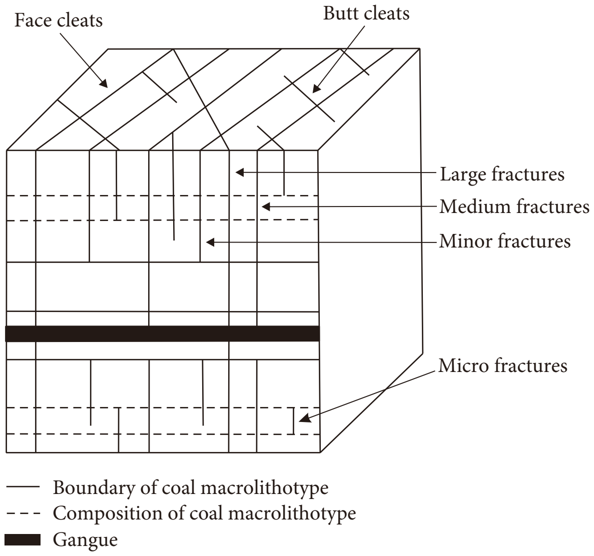


Figure 1: Classification of coal seam fractures [13].

2. A New Mode of VFS in Coal Seams

The subsurface in situ observations of coal seams in coal mines show that coal seams generally develop VFSs. The VFS can be identified by the naked eye, including exogenetic fractures, interlayer fractures, gas-expanding fractures, and cleats. Through in situ observations of coal seams, the development characteristics of VFSs are as follows.

2.1. Hydraulic Fractures.

2.1. Hydraulic Fractures. Understanding the fracture geometry, scale, and distribution of hydraulic fracturing can provide a reference for evaluating the hydraulic fracturing effect of CBM wells and optimizing the target fracturing zone and fracturing process.

In situ observation of the hydraulic fractures exposed in the coal mining process is employed to understand the occurrence of hydraulic fractures in coal seams. The results show that there are three types of hydraulic fractures in CBM reservoirs, namely, vertical fractures, horizontal fractures, and T-type fractures (Figure 1). The fracture length is generally from 10 to 30 m, and the height varies from 2 m to 5 m [22]. The width is usually less than 10 cm. In addition, the surfaces of vertical hydraulic fractures are rough and uneven. However, the surfaces of horizontal hydraulic fractures are smooth and flat.

In addition, most hydraulic fractures are only developed in undeformed coal and cataclastic coal and are rarely distributed in fragmented coal and mylonitic coal [25–27]. For undeformed coal seams, hydraulic fractures have a large scale, but the number of fractures is small. However, in tectonically deformed coal, the number of hydraulic fractures is

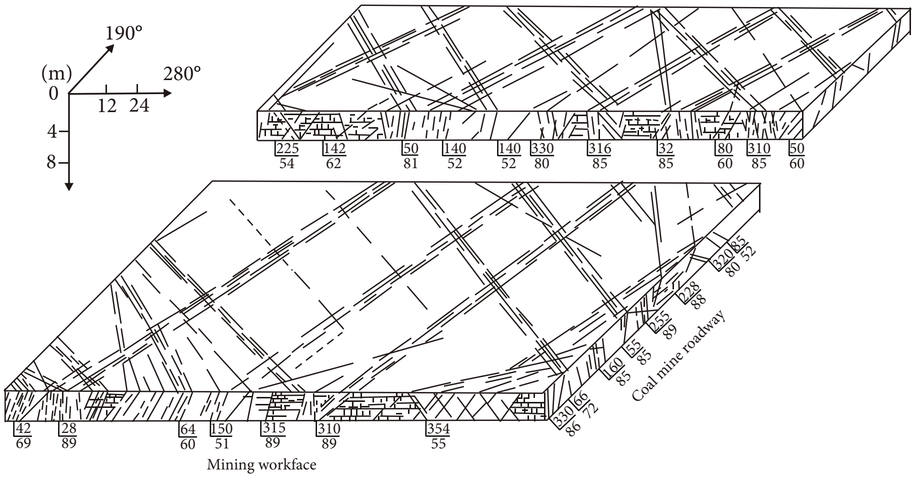


Figure 2: Exogenetic fractures in coal seams in the southern Qinshui Basin (revised from [15]).

greater than that in undeformed coal, but the size of the fractures is smaller.

2.2. Exogenetic Fractures. Exogenetic fractures are formed by tectonic stress action on coal seams, and their occurrence is usually matched with high-level faults or folds. This kind of fracture exists widely in coal seams. They intersect with the stratifications at various angles, and their occurrence generally agrees with the direction of nearby faults. Exogenetic fractures can develop in any part of coal seams [28]. The surfaces of exogenetic fractures usually have uneven sliding traces, mostly displaying feathery, wavy but also relatively smooth features. Fillings such as multistage limestone and clay minerals are often found in exogenetic fractures, which explains why these fractures are the main channels for internal and external fluid exchange. Based on in situ observations in coal mines, the distribution characteristics of exogenetic fractures in coal seams are shown in Figure 2.

2.3. Interlayer Fractures. As the sedimentary environment changes in the coal formation process, several gangue layers usually develop within coal seams. The thickness of each gangue is generally not more than 10 centimeters, and the distribution along coal seams is stable. Because of the significant difference in rock lithology between gangue and coal, the interface between gangue and coal can form a weak cohesive zone, which can develop interlayer fractures. Additionally, interlayer fractures also exist along the stratification within coal seams. False roofs can develop between the coal seam and roof, which are generally carbonaceous shale with a thickness of tens of centimeters. Due to the low mechanical strength of false roofs, interlayer fractures can be distributed in the false roofs. In the coal mining process, coal easily falls off along the interlayer, which also demonstrates that the existence of interlayer fractures makes the coal seam adhesion very weak.

2.4. Gas-Expanding Fractures. The morphology and scale of gas-expanding fractures are similar to those of exogenetic fractures, while the occurrence and surface pattern are very similar to those of cleats. Preliminary studies have shown that these kinds of fractures are tensile and formed by the outward expansion of fluids during CBM formation. Gas-expanding fractures significantly influence the rock physical properties of coal seams and have symbolic significance for the formation, enrichment, and preservation of CBM reservoirs. Gas-expanding fractures are usually seen in bright and semibright coal. The height is generally between several centimeters and tens of centimeters but is not developed or poorly developed in dull coal (Figure 3).

2.5. Cleats. Cleats in coal seams are also termed endogenetic fractures. There are apparent equal or nearly equal distances among cleats (Figure 3). Cleats are perpendicular to the bedding plane, with a flat surface pattern, and sometimes are filled with minerals. Cleats are formed by the internal tension caused by the changes in the internal structure and uniform shrinkage of the gelation material influenced by the variations in the temperature and pressure in coal during coalification. Therefore, the development of cleats is mainly restricted in vitrain coal, and cleats are commonly distributed in bright coal and semibright coal. The cleats in middle-rank coal are the most developed, with 30 to 40 cleats within 5 centimeters, sometimes up to 50 or 60. Cleats are usually not developed in low- and high-rank coal, generally less than 15 within 5 centimeters.

The categories and characteristics of the VFS in coal seams are listed in Table 1.

3. Discussion on the Implications of the VFS for CBM Production

3.1. Flow Channels of CBM, Formation Water, and Coal Fines. The development characteristics of VFSs significantly determine the difficulty of CBM seepage within reservoirs. VFSs with high density, good connectivity, large width, and long extension distance are more conducive to the seepage and output of gas and formation water. Large amounts of fractures are developed in tectonically deformed coal because of the intense stress action. However, the mechanical properties of tectonically deformed coal are sharply weakened due to damage to the coal body. The fractures

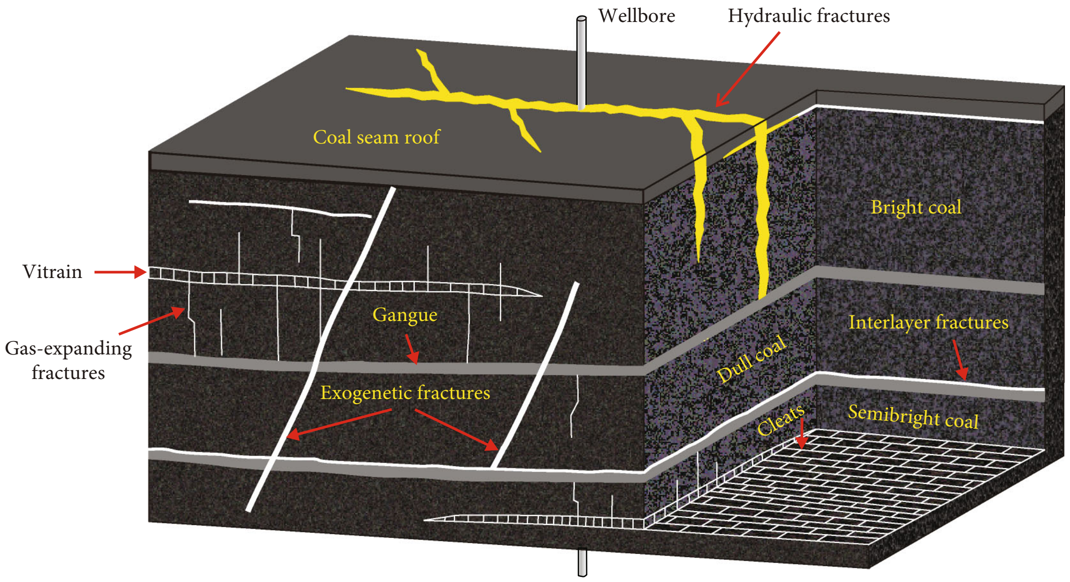


Figure 3: Sketch of the VFS in coal seams.

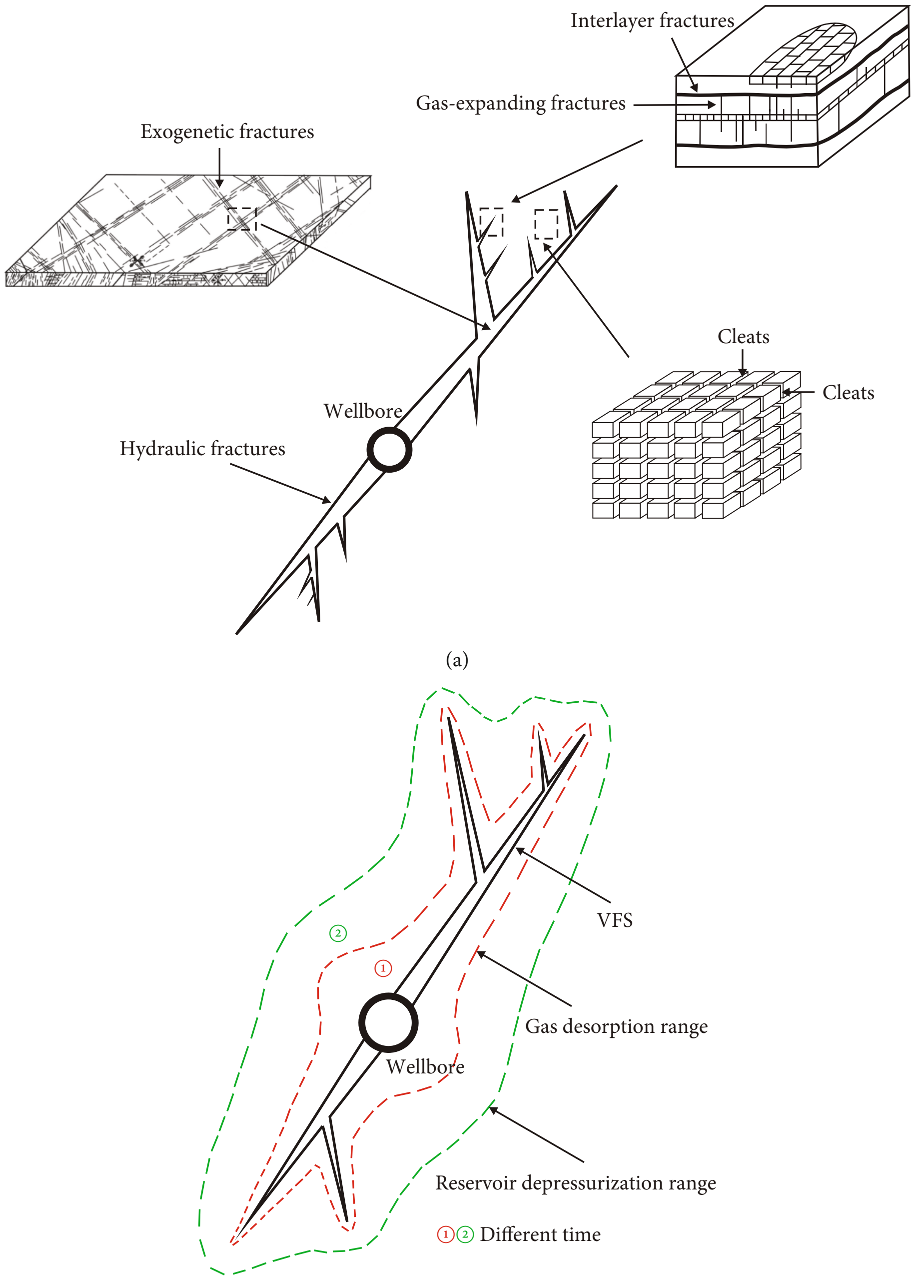
Table 1: VFS classification in coal seams.

Channel type	Distribution positions	Space extent range	Connection role	Level
Hydraulic fractures	Around the wellbore	A few meters to tens of meters	Wellbore, exogenetic fractures, and interlayer fractures	I
Exogenetic fractures	Any positions of coal seams	A few meters to hundreds of meters	Hydraulic fractures, interlayer fractures, and gas-expanding fractures	II
Interlayer fractures	Gangue, roof, interlayers	A few meters to hundreds of meters [29]	Connect hydraulic fractures, exogenetic fractures	III
Gas-expanding fractures	Bright coal and semibright coal [15]	Several centimeters to tens of centimeters	Connect hydraulic fractures, exogenetic fractures, and cleats	IV
Cleats	Specular coal and bright coal [30]	Several millimeters to several centimeters	Connect the microfractures in the coal matrix	V

are short and narrow and are filled with many carbonate rocks or clay minerals. Effective fractures that widely communicate with the wellbore are challenging to form. These unconnected fractures in tectonically deformed coal can hinder the seepage of coal seam fluids, which restricts the production volume of CBM wells. Therefore, although the VFS is developed in tectonically deformed coal, the flow conductivity is not strong.

The VFS is also the main channel of coal fine migration during CBM production. The precondition that coal fines migrate into the wellbore is that the fractures have good connectivity. The coal fines produced by CBM wells mainly come from the primary coal fines [31, 32]. There are two main occurrence places. One is in the stratification above the soft coalbed, and the other is in the fracture system connected with the tectonic coal inside the coal body. Most coal fines move into the wellbore through the VFS, with a small amount entering the wellbore directly [33]. Due to the tortuous characteristics of the VFS, the coal fines produced by vertical wells are from the fractures near the wellbore and the fracture channel. Whether there is a soft coalbed around the wellbore is crucial in creating coal fines. The coal fines are relatively developed and quickly produced if they pass through the tectonism-developed zone. For horizontal CBM wells, the migration channel of coal fines mainly depends on the horizontal borehole. Suppose they pass through the nearly vertical tectonism-broken area. In that case, the horizontal well can directly collapse and expand the hole, and the coal fines are relatively easy to separate and migrate through the horizontal well [17]. If the soft coalbed is located above the horizontal branch of the horizontal CBM wells, the horizontal borehole easily collapses, which will also cause the output of coal fines [34, 35]. Therefore, CBM horizontal wells produced more coal fines than CBM vertical wells.

3.2. Determination of the Reservoir Permeability and Transmission of the Reservoir Pressure and Gas Desorption Range. Permeability represents the conductivity of CBM reservoirs. Effective permeability is conducive to the output of CBM. The effective permeability of CBM reservoirs is determined by the development degree of the VFS in coal seams. As unconventional natural gas, CBM reservoirs generally have low permeability. Reservoir permeability is generally



(a)

(b)

Figure 4: Transmission of reservoir pressure and gas desorption range (revised from [43]): (a) reservoir pressure transmission in VFS; (b) variations of reservoir depressurization and gas desorption range in the horizontal section.

obtained by testing coal seam samples in the laboratory. However, the sample permeability has difficulty reflecting the effective permeability of CBM reservoirs, as the laboratory conditions dramatically differ from the actual geological conditions. For areas with in situ observation conditions, coal seam permeability can be directly analyzed by observation and measurement. The relationship between the surrounding rock and VFS in coal seams can be obtained through surface structural joint mapping if the VFS cannot be directly observed. The development characteristics and permeability of the VFS in coal seams can also be analyzed [36].

In addition, the permeability of the VFS will change with the output of CBM. In the dewatering stage and gas-water two-phase flow stage, the fluid pressure in the VFS decreases. The fractures are gradually closed under effective stress, and the coal seam permeability is decreased [37–39]. In the stable gas production stage and declining gas production stage, due to the matrix shrinkage effect, the fracture width and coal seam permeability both increase [40–42].

In the process of reservoir depletion, the VFS in coal seams provides spaces for pressure transmission. Therefore, the development of the VFS, mainly hydraulic fractures and exogenetic fractures, significantly impacts the depressurization

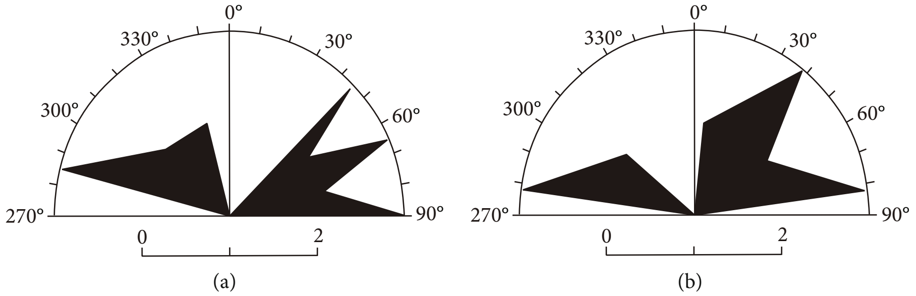


Figure 5: Relationship between the orientation of principal stress and vertical fractures in Sihe mine: (a) maximum principal stress direction; (b) vertical fracture direction.

range. The coal seam pressure drop is propagated along the VFS and changes in the temporal and spatial dimensions.

In CBM production, the basic transmission modes of the reservoir pressure include water transfer and gas transfer [43]. In the early dewatering stage, the produced water mainly comes from hydraulic fractures and exogenetic fractures (Figure 4(a)), where water transmission mainly occurs. Due to the high permeability of the VFS in coal seams and the rapid pressure drop, this stage is generally short. At the gas-water two-phase flow stage, the water production rate gradually decreases while the gas production rate gradually increases. Therefore, the water transmission in the VFS is slowly weakened, and the gas transmission is slowly enhanced. In the stable gas production stage, the pressure transmission in the VFS is almost entirely contributed by gas transmission rather than water transmission.

With the decreased reservoir pressure, the methane in the coal matrix desorbs continuously, and the gas desorption range gradually expands around the VFS, as shown in Figure 4(b). The range and degree of reservoir pressure transmission in CBM production determine the gas desorption range of CBM. Therefore, the geometry, scale, and strike of the VFS in the coal seam significantly affect the distribution of the gas desorption range.

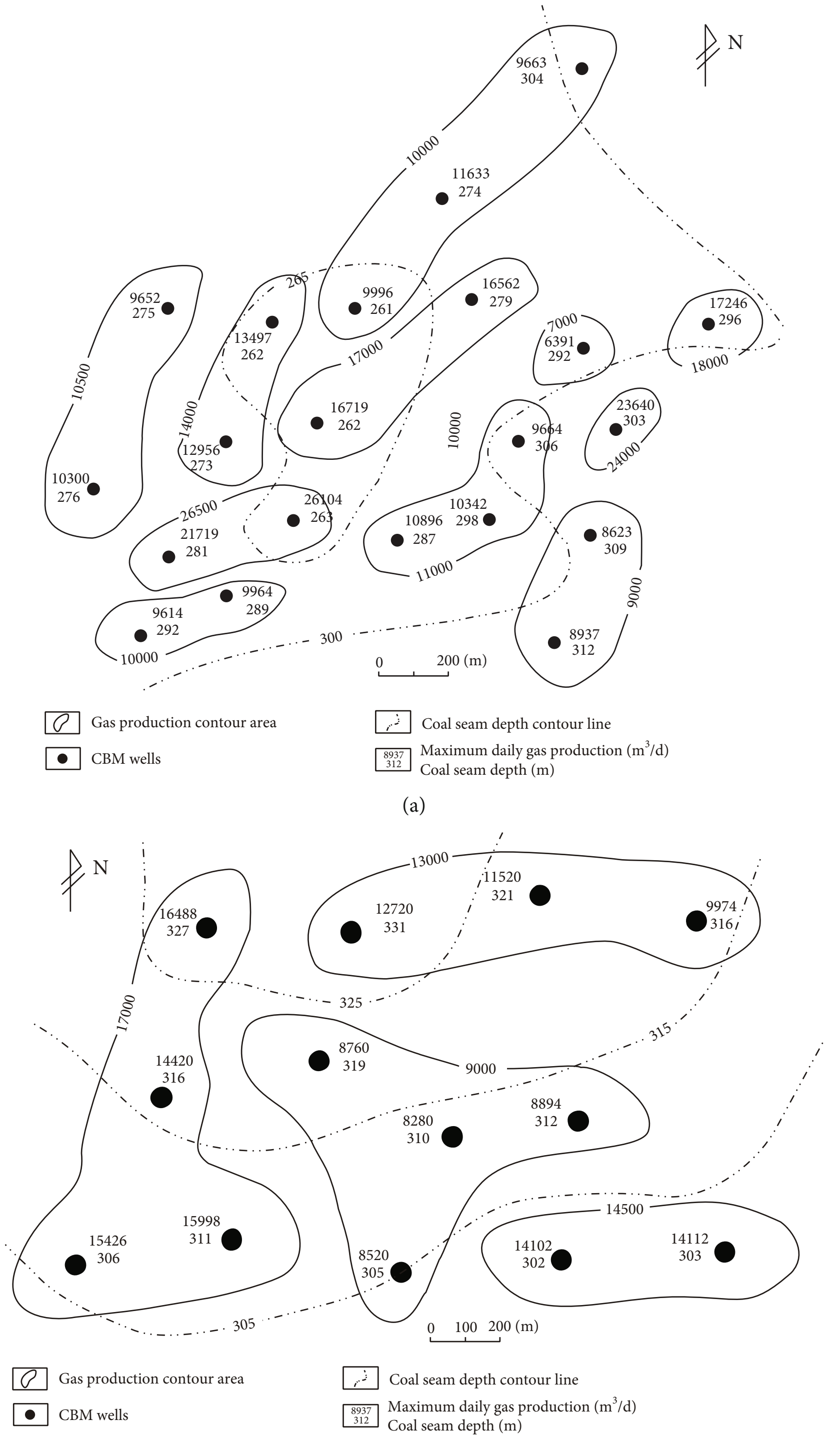
3.3. Interaction between Hydraulic Fractures and the Natural VFS. The underground observations show that the vertical fracture orientation is generally consistent with the VFS. For example, the direction of the exogenetic fractures in the Sihe and Chengzhuang coal mines, North China, is NEE and NWW, as shown in Figure 5. This indicates that the orientation of vertical hydraulic fractures is consistent with that of the principal stress in this area, which is NEE and NWW. As the regional tectonic stress controls the development of the exogenetic fracture system, the orientation of hydraulic fractures is also generally consistent with that of the regional tectonic stress [44]. In addition, the underground observation of hydraulic fractures shows that the horizontal hydraulic fractures mainly extend along the interlayer fractures of the VFS in coal seams [45]. In our opinion, the fracturing fluids injected into the formation preferentially extend along the exogenetic fractures and interlayer fractures due to the weak cementing strength in these fractures [46, 47]. Therefore, our field observations and field test results can explain this phenomenon.

The exogenetic fractures and interlayer fractures significantly affect the expansion of the central hydraulic fractures, and the gas-expanding fractures and cleats usually control the branch of hydraulic fractures (Figure 4). In addition, if the gas-expanding fractures and cleats are very developed, fracturing fluids could leak off, and high fluid pressure is lost. This is why fracturing fluids easily leak off during fracturing in the coal seam. Furthermore, the scale of hydraulic fracture propagation is significantly limited, and the stimulation effect is obviously reduced.

3.4. Influences on the Productivity Distribution of CBM Wells. The VFS in coal seams largely determines the heterogeneity of CBM reservoirs [48, 49]. To understand the relationship between VFS development and the productivity of gas wells, the distribution characteristics of CBM well productivity are investigated. The study area is located in the Jincheng mining area, the southern Qinshui Basin, North China. Coal seams in the study area are nearly horizontal. The thickness of the coal seam is large with an average value of more than 5 m. The burial depth of the coal seam is less than 800 m. In the study area, the VFS is developed, especially the large exogenous fractures and gas-expanding fractures. There are hundreds of typical CBM production wells located in this area, which provide abundant production data for the research of productivity distribution.

The maximum daily gas production is one of the crucial parameters to characterize the productivity of CBM wells. In addition, the total gas production volume and average gas production volume are difficult to obtain, as the production time and the production stage of these CBM wells differ. Therefore, the parameter of maximum gas production was employed for the statistical analysis. Our study indicates that the maximum daily gas production of CBM wells has pronounced directivity, with a bounded-type, L-type, and T-type pattern (Figure 6). We find that the maximum daily production of adjacent wells usually differs. Furthermore, for any development area, no more than five adjacent wells will have close maximum daily gas production. Therefore, the direction of the maximum daily production distribution of wells is closely related to the development of the VFS.

We think that the types of productivity distribution of CBM wells are closely related to the geometry, scale, and orientation of VFSs with different levels. The maximum daily production distribution of a bounded-type CBM well is



(a)

(b)

Figure 6: Coal seam maximum dairy production distribution: (a) bounded type; (b) L-type and T-type.

determined by the dominant direction of the hydraulic fractures and exogenetic fractures. The distribution of the maximum daily gas production in a T-type CBM well shows that two large-scale fractures are developed and well connected (Figure 6(b)), such as exogenetic fractures. The distribution of the maximum daily gas production in an L-type CBM well shows that gas-expanding fractures are connected in two directions (Figure 6(a)) [50]. In addition, the maximum daily production of a few CBM wells is significantly different from that of the surrounding gas wells, which means that the wellbore does not communicate with a large-scale VFS.

Therefore, drilling holes should be arranged in areas where the VFS develops, leading to good connectivity. Moreover, where there are CBM wells, infill wells enhancing gas production should be arranged in the VFS along with nearby high-yield gas wells.

4. Conclusions

According to the in situ observations and field tests, a new mode of VFS is proposed. Furthermore, the development characteristics of the VFS and its influences on CBM production are discussed. The main achievements in this work are as follows.

Depending on the geometry, orientation, scale, distribution, and connectivity characteristics, the VFS in coal seams can be divided into five subclasses, including hydraulic fractures, exogenetic fractures, interlayer fractures, gas-expanding fractures, and cleats. The VFS provides the channel for the migration of CBM, formation water, and coal fines. It determines the flow conductivity of reservoirs and controls the propagation of the reservoir pressure and the gas desorption range. The propagation of hydraulic fractures is affected by the development of exogenous fractures. We find that the exogenetic fractures and interlayer fractures dominate the expansion of the central hydraulic fractures, and gas-expanding fractures and cleats usually control the branch of hydraulic fractures. The VFS influences the productivity distribution for CBM wells, with a banded, L-shaped, or T-shaped pattern. This indicates that the development of the VFS shows the strong heterogeneity of coal seams.

This study presents a theoretical foundation for understanding the development characteristics of artificial and natural fractures in coal seams and their influences on gas flow. Furthermore, our work guides the selection of favorable CBM blocks and CBM exploitation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (nos. U19B2009 and 52204125), Science and Technology Think Tank Young Talent Program (no. 20220615ZZ07110307), and the National Science and Technology Major Project of China (no. 2016ZX05067001-007). In addition, special thanks are due to PetroChina Huabei Oilfield Company for providing the production data of CBM wells. These supports are gratefully acknowledged.

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