IN THE FIELD

Effects of structural fracture and in situ stress combination characteristics on the production of coalbed methane wells: A case in the Mabidong block, China

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Abstract
Similar drilling, fracturing, and drainage techniques were adopted in the early stage of developing coalbed methane (CBM) in the Mabidong block, but the production of adjacent CBM wells was significantly different. The effects of coal seam depth, thickness, reservoir pressure, the ratio of desorption pressure and reservoir pressure, and gas content on the production of CBM wells are systematically studied. It is found that these parameters are not the critical control factors. The data of 107 observation points were obtained by using high-precision structural fracture mapping technology, and four structural fracture development zones were delineated in the Mabidong block. Simultaneously, according to the in situ stress state, the Mabidong area is divided into an in situ stress tension state, and in situ stress compression state, and an in situ stress transition state. Based on structural fracture development and in situ stress state characteristics, four kinds of matching relationships are found: (1) Structural fracture development and in situ stress state are tension or transition state. (2) The structural fractures are developed, but the in situ stress state is in the compression state. (3) The structural fracture is not developed, and the in situ stress state is tension or transition state. (4) The structural fractures are not developed, and the in situ stress is in the compression state. The comprehensive analysis of the 19 CBM well production shows that the CBM well production is high when the structural fracture dense area and the in situ stress tension and transition area coincide, while the CBM well production is low when other matching relationships. The matching relationship’s accuracy in controlling the CBM well production is 89%. The characteristics of structural fracture development and in situ stress state are the combined control factors of CBM well production in the Mabidong block.

KEYWORDS
CBM development, high-precision structural fracture mapping, in situ stress state, production factor, structural fractures
According to the 4th resource evaluation by the Ministry of land and resources, China’s CBM geological resources, 30.05 trillion m$^3$, and recoverable resources, 12.5 trillion m$^3$, rank the third in the world. In 2018, the number of CBM wells in China exceeded 18 thousand, but the daily production of single wells was generally low, with 300-m$^3$ vertical wells and 1000- to 2000-m$^3$ horizontal wells, far lower than that of the United States, Australia, and Canada. Therefore, the low production of the single well of CBM has become a bottleneck problem restricting CBM industrialization development in China.

Many researchers used statistical methods or geological analogy to research the production characteristics of different CBM basins or blocks and summarized many factors that affect CBM well production. The researchers studied the CBM well production characteristics in Sand Wash and the San Juan Basin and concluded that the groundwater, permeability, structural, and depositional factors were critical factors affecting CBM well production. Ayers considered that the vital elements to CBM well production were the maceral composition, the fracture density, the gas content, the in situ stress, the permeability, and the hydraulic fracturing process. Su summarized six key parameters that affect CBM well production: the structural characteristics, the sedimentology, the permeability, the gas content, the coal rank, and the hydrodynamics. Sang thought gas content and permeability were the most important geological factors. Besides the above factors, Lv and Chen believed that the structural setting and hydrogeological condition are also two critical factors that dominate CBM well productivity. Chen summarized three types of high gas production models: updip of the monocline, the axial part of the anticline or nose structure, and the structural high far from the normal fault. Peng studied the Shizhuangnan block of the southern Qinshui basin; he thought that the sealing ability of roof and groundwater flow affected CBM well productivity. Some scholars thought the reservoir pressure, permeability, structural curvature, and coal structure were the key factors. Some scholars believed that the Poisson’s ratio, Young’s modulus, the Langmuir pressure, and methane’s initial pressure were critical. In addition to that, engineering factors, such as hydraulic fracturing and horizontal drilling technology, will affect production. Many factors affect the CBM well production, so some scholars use the gray system theory and Back Propagation neural network methods to study the factors.

Many scholars have summarized the control factors; they found that different blocks have different control factors. Among the many factors, permeability and gas content are the most critical factors. Other geological factors, such as coal rank, coal seam thickness, buried depth, hydrological conditions, coal structure, fracture characteristics, structural characteristics, and sedimentary characteristics, will impact these two key parameters. The gas content is higher in areas with better sealing conditions, and permeability has become a key parameter restricting production. The coal reservoir’s seepage channel comprises structural fractures, cleat systems, and micro-fractures. High-rank coal reservoirs’ permeability is lower than low-medium rank coal reservoirs. However, the Qinshui Basin has experienced three stages of tectonic movement, and many structural fractures have formed in the coal reservoirs, which significantly increased the permeability of the coal reservoir. Many scholars have also paid attention to this problem and proposed the control effect of structural and fracture characteristics on CBM well production.

Different scholars have adopted other research methods, identification methods, and prediction methods of structural fractures. Some scholars qualitatively analyzed structural fractures’ development characteristics from the geological structure perspective. Many scholars use multiple experimental techniques to study structural fractures, such as optical microscopy (OM), scanning electron microscopy (SEM), nuclear magnetic resonance (NMR), X-ray computed tomography (X-CT), and stereomicroscope. In some CBM basins, some macroscopic observation methods have been used to study natural fractures, such as underground coal wall observations, core log analyses, and image logging interpretation. Geological modelings, mathematical modeling, and then numerical simulation methods are also used to study structural fractures. The above research methods are usually carried out using laboratory tests, core observations, logging, underground coal wall observations, geological modeling, mathematical modeling, and then numerical simulation methods, which can provide a certain degree of understanding of the development characteristics of local structural fractures. However, the above methods are limited by the number of samples and observation range, and the coal samples have strong heterogeneity. Therefore, the results obtained by the above methods cannot fully represent the whole CBM development block.

The CBM well production is also affected by engineering factors. However, in the Mabidong block, similar development technology was adopted in the early stage. The same drilling and completion technology, hydraulic fracturing, and drainage systems develop CBM vertical wells. In other words, the engineering measures of CBM wells are the same, but there are 1-2 orders of magnitude differences in gas production. Geological characteristics cause this difference.
Gas content and permeability are the two most essential factors in the geological characteristics affecting the CBM well production. If the gas content in a CBM development block is the same, permeability is the critical factor affecting the production. The combined structural fracture and in situ stress control the permeability, impacting the CBM well production. This paper used a high-precision structural fracture mapping technique, and in situ stress testing technology, the geological characteristics, and production data were comprehensively analyzed. The research results facilitate establishing a reasonable well distribution principle, improve CBM recovery, and increase the number of high-yield CBM wells.

2 | GEOLOGICAL SETTING

The Mabidong block is located in the south of the Qinshui Basin, as shown in Figure 1. The main coal seams are No. 3 and No. 15. The Liujiagou formation is mainly exposed on the surface, as shown in Figure 2. The study area is a northwest uplift southeast inclined monoclinic structure, and the occurrence of coal seam changes little. The basin’s internal structural deformation is relatively simple, with the secondary anticline and syncline distributed in parallel and arranged alternately, followed by the fault structure. The main faults are NNE and NE normal faults, and the dip angle is generally greater than 60°.

The net thickness of the No. 3 coal seam is 5.8-6.6 m, with an average of 6.2 m. The vitrinite reflectance (Ro) of the No. 3 coal seam is 2.68%-3.0%, with an average of 2.86%. The moisture content is 0.87%-1.41%, with an average of 1.25%; the ash content is 11.21%-23.42%, with an average of 16.24%, and the volatile content is 9.16%-10.91%, with an average of 9.62%. The gas content is 15.70-27.82 m³/t, with an average of 20.40 m³/t; Langmuir volume is 25.67-36.15 m³/t, with an average of 30.32 m³/t; Langmuir pressure is 2.00-2.56 MPa, with an average of 2.25 MPa; and gas saturation is 72.19%-97.24%, with an average of 84.41% (Table 1).

The net thickness of the No. 15 coal seam is 3.2-10 m, with an average of 5.9 m, and the buried depth of the coal seam is 1000-1300 m. The vitrinite reflectance (Ro) of coal seam 15 is 2.65%-2.90%, with an average of 2.76%. In the
industrial analysis, the moisture content is 0.54%-1.33%, the average is 0.95%, the ash content is 11.49%-24.16%, the average is 17.99%, the volatile content is 8.42%-10.68%, and the average is 9.57%. The gas content is 14.25-19.50 m³/t, with an average of 17.80 m³/t; the Langmuir volume is 30.70-35.61 m³/t, with an average of 33.99 m³/t; the Langmuir pressure is 1.72-2.28 MPa, with an average of 1.99 MPa; the gas saturation is 56.60%-58.18%, with an average of 63.10%. The coal seam net thickness, vitrinite reflectance, moisture content, ash content, volatile content, gas content, Langmuir′s volume, and Langmuir′s pressure of No. 3 coal seam and No. 15 coal seam are similar, but the buried depth of No. 15 coal seam is about 100 m deeper than that of No. 3 coal seam.

3 | PRODUCTION CHARACTERISTICS AND FACTOR ANALYSIS

The CBM well production follows drainage and pressure reduction. Generally, it can be divided into single-phase water flow, two-phase gas-water flows, and single-phase gas flow. In Mabidong block, vertical wells development mode was adopted, mainly drainage coal seam 3 or coal seam 15, among which well M57 was the multilayer drainage coal seam 3 and 15. In this area, the selected wells’ production time was over 24 months. Thus, the CBM wells have entered the stage of stable production. The average daily gas production is calculated.
according to the comparison between the total gas production and the days of gas production in the stable production period. Production data for 19 wells are shown in Table 2. The average gas production is 786 m³/d, and the average water production is 3.90 m³/d. Nine CBM wells are more than 1000 m³/d, and three wells are less than 100 m³/d. Thirteen CBM wells mainly develop coal seam 3, and five wells specifically exploit coal seam 15. Only one well produces coal seam 3 and coal seam 15 at the same time.

CBM well production is controlled by many factors, including engineering and geological factors. Similar drilling, fracturing, and drainage techniques were used in the early stages of development, but CBM well production
from adjacent varied significantly. Therefore, engineering factors are not the main reason for the huge difference in production between adjacent CBM wells. Instead, there are many geological factors, so it is necessary to analyze each factor and production's relationship and determine the most critical geological factors. Therefore, the whole research process is studied: (1) The relationship between coal seam depth, thickness, reservoir pressure, temporary reserve ratio, gas content, and CBM well production. (2) Using a structural fracture mapping technique and in situ stress testing technology, the geological characteristics and production data were comprehensively analyzed. As a result, the key factors influencing the production of CBM were determined in the Mabidong block.

3.1 The depth of coal seam

The coal seam depth is related to gas content, in situ stress, permeability, and reservoir pressure. Generally, with the increase of buried depth, the gas content increases, the in situ stress increases, the permeability decreases, and the reservoir pressure increases. Figure 3 shows that the buried depth of the coal seam is between 981 m and 1377 m, and the relationship between the buried depth and the gas production of the CBM well is relatively scattered, showing no correlation. It indicates that the buried depth has little correlation with the production of CBM well. The buried depth of high-yield wells with output more than 1000 m³/d is distributed from 998 m to 1273 m, while that of low-yield wells with production less than 1000 m³/d is distributed from 981 m to 1377 m, so the buried depth is not a significant control factor in the study area.

3.2 Thickness

Coalbed methane is the associated product in the process of coal seam formation. The thicker the coal seam is, the richer the gas source is, and the stronger the gas supply capacity is under the same conditions. Therefore, the thicker the coal seam is, the greater the gas production will be. Figure 4 shows that there is no necessary relationship between coal seam thickness and gas production. In the Mabidong block, it is not shown that the larger the coal seam thickness, the higher the gas production. For high-yield wells with gas production greater than 1000 m³/d, the coal seam thickness ranges from 5.05 m to 10.6 m, with an average of 6.56 m; for low-yield wells with gas production less than 1000 m³/d, the coal seam thickness ranges from 4.2 m to 7.4 m, with an average of 5.9 m. Therefore, coal seam thickness is not the control factor of gas production in the study area.

3.3 Reservoir pressure

Coal reservoir pressure has a crucial influence on the gas content and gas occurrence state of the coal seam and the energy of gas and water flowing from fracture to wellbore. The reservoir pressure is generally obtained through well test technology. The scatter plot is made using gas production and reservoir pressure. Furthermore, it is found that there is no apparent relationship. With the increase of reservoir pressure, there is no noticeable increase in gas production, as shown in Figure 5. The reservoir pressure for high-yield wells with gas production greater than 1000 m³/d is 9.4-13.2 MPa, with an average of 11.2 MPa; for low-yield wells with less than 1000 m³/d, the reservoir pressure ranges 5.74-13.78 MPa, with an average of 9.82 MPa.

3.4 Ratio of critical desorption pressure to reservoir pressure

For the gas supersaturated coal seam, as long as the coal reservoir pressure drops, there will be adsorption gas desorption from the coal seam; for the gas under-saturated coal seam, it must be reduced below the critical desorption pressure before the adsorption gas can be desorbed. The higher the ratio of critical desorption pressure to reservoir pressure, the more conducive to gas recovery. As shown in Figure 6, the relationship between the ratio and gas production is weak. Therefore, the ratio is not an essential gas production factor.

3.5 Gas content

Coal seam gas content is one of the important indexes for evaluating the CBM development area, and it is also essential basic data for calculating CBM resource reserves. The gas content is between 10.8 and 27.8 m³/t, with an average of 19.1 m³/t, as shown in Figure 7. There is no inevitable relationship between the gas content and the production. Of course, if the coal seam gas content is higher, it is also beneficial to the production of CBM wells. Therefore, in the CBM well location selection stage, the areas with high gas content are selected. However, high gas content and high production are inconsistent.

Through the study of coal seam depth, thickness, reservoir pressure, the ratio of critical desorption pressure to reservoir pressure, and gas content, it is found that these general parameters have no apparent relationship with the production of CBM wells. The necessary geological conditions for the high production wells are the simultaneous presence of high gas content and high permeability. Currently, permeability is generally used as an indicator for the classification of
reservoirs. Within a block, the gas content is not much different. However, in high permeability areas, generally, CBM well production is also relatively high. For the Mabidong block, the gas content is mainly distributed in 16-22 m³/t. Only three wells have been tested and obtained permeability parameters in this block, but it is impossible to conduct a comparative study on the entire block.

4 METHODS

Reservoir permeability is controlled by the fracture system and the in situ stress field. The fracture system is the migration and seepage channel of coalbed methane, while the in situ stress field handles the fracture’s closure; the matching relationship between the development characteristics of the fracture and the in situ stress field determines the permeability level.

The permeability of coal reservoirs is determined by the seepage capacity provided by its fracture channels. The seepage channels are composed of structural fractures, endogenous fractures (face cleats and butt cleats), and microfractures determining permeability. Structural fractures are the channel’s primary fractures among the above fractures, and their development is critical for seepage capacity. Many practical studies have proved that rock layers belonging to the same tectonic layer are subject to tectonic stress and produce similar fractures. The development density of fractures is controlled by lithology, rock layer thickness, structural location, and tectonic stress. The surface joints and fractures develop densely in rocks, and at the same depth underground, the joints are also denser than rocks in other areas. The surrounding
rocks and coal reservoirs in coal-bearing strata belong to the same structural layer and tectonic stress. Therefore, similar structural fractures will occur in the surrounding rock and coal reservoirs. In the areas with dense surface structural fractures, the development degree of structural fractures in coal reservoirs is also denser than in other areas.

Based on the above understanding, this paper uses high-precision structural fracture mapping technology and in situ stress field analysis technology to conduct a detailed study on the development and closure of the primary fractures and finds that it is the critical main controlling factor for the production of CBM wells.

### 4.1 The high-precision structural fracture mapping technique

This paper use of structural fracture mapping method for CBM wells has multiple structural fracture observation point control. According to the regulation, the requirements for geological mapping with a scale of 1:10 000 are as follows: The number of geological observation points per square kilometer in the simple structural area is 20-30, 30-45/km² in medium structural area, 45-60/km² in complex structural area, and >60/km² in extremely complex structural area. The setting distance between observation points is 100 m, structural fracture observation points per square kilometers for 100, more than the number of the coalfield geological mapping specification requirements one order of magnitude, so-called “high-precision structural fracture mapping.” The photograph of the high-precision structural fracture mapping technique is shown in Figure 8.

### 4.2 The in situ stress field analysis technology

In situ stress measurement is essential in CBM development, closely related to permeability and recovery. Generally, in CBM development, injection/falloff testing is used to obtain in situ stress data. The in situ stress test can obtain data such as closing pressure and then use the formula to calculate the triaxial stress. The calculation formula is as follows:

\[
\sigma_h = P_c \tag{1}
\]

\[
\sigma_H = 3P_c - P_f - P_o + T \tag{2}
\]

\[
\sigma_v = 10^{-3} \rho g h \tag{3}
\]
where $\sigma_h$ is the minimum horizontal principal stress, MPa; $P_c$ is the closure pressure, MPa; $\sigma_H$ is the maximum horizontal principal stress, MPa; $P_f$ is the fracture pressure, MPa; $P_o$ is the reservoir pressure, MPa; $T$ is the coal seam tensile strength, MPa; $\sigma_v$ is the vertical ground stress, MPa; $\rho$ is the rock’s average density, $10^3$ kg/m$^3$, generally 2.7; $h$ is the buried depth of the coal seam, m, note that “$T$” in formula 2. The tensile strength “$T$” is a parameter obtained from the results of laboratory tests. The test method is according to “Methods for determination of physical and mechanical properties of coal and rock” (GB/T 23561.10-2010).

The stress state of the reservoir in the study area was analyzed using the lateral stress coefficient, namely:

$$\lambda = \frac{\sigma_H + \sigma_h}{2\sigma_v} \quad (4)$$

5 | RESULTS AND DISCUSSIONS

The seepage channels of coal reservoirs are mainly composed of pores, microfractures, face cleats and butt cleats, structural fractures, and artificial fractures. Structural fractures are also called joints. They are the product of paleo-stress evolution, and the development characteristics of the major fractures in the system determine the permeability of the reservoir. From a spatial point of view, the in situ stress field controls the development characteristics of regional tectonic traces and defines the structural fracture system. From the time point of view, the paleo-in situ stress field determines the occurrence and development of structural fractures in coal reservoirs. The current in situ stress field controls the opening and closing degree of coal reservoir fractures. In time and space, in situ stress and structural fractures’ combined action determine coal reservoirs’ seepage capacity.

5.1 | Characteristics of structural fractures

By measuring 107 observation points (Table 3), it is found that the structural fractures in the bedrock mainly develop in 2 directions. The dominant directions of structural fractures are NE direction in the west of the study area, NE direction, and NW direction in the middle and the east region. The main direction of structural fractures in the
entire study area is NE, followed by NW, as shown in Figure 9.

The relationship between the same lithology or thickness is mainly selected. First, the layer thickness or lithologic parameters are obtained by the proportional relationship between the structural fracture density. Then, the structural fracture density measured in the field is corrected based on the same quasi-layer.

The linear density of structural fractures in surface outcrops is controlled by lithology and rock thickness. The rock thickness, lithology, linear density, and direction of different structural fracture observation points in the study area are obtained through high-precision structural fracture mapping technology. The widely developed 0.8-m fine sandstone is selected as the standard in the study area, and the linear density of structural fractures at all observation points is calculated uniformly. If there are 2-3 groups of structural fractures in the observation points, they also need to be converted uniformly. The linear density of all structural fractures in the observation point is superimposed as the linear density grade of structural fractures at this observation point. According to the joint density characteristics of each observation point, it can be divided into structural fracture development points, medium development points, and not development points. These observation points are projected onto the map to circle the structural fracture development points. The study area has four fracture development zones: the east, middle, west of the center, and west, as shown in Figure 10. In the area of the fracture development zones, the structural fracture is relatively dense. Outside the region, structural fractures do not dense.

5.2  Characteristics of the in situ stress

Equations (1)-(3) calculate the in situ stress value. Then, the maximum horizontal principal stress ($\sigma_{H}$), minimum horizontal principal stress ($\sigma_{h}$), and vertical stress ($\sigma_{v}$) are calculated using the formula. Finally, the lateral pressure coefficient was calculated using formula 4. The calculation results are shown in Table 4.

The side pressure coefficient in the east is less than 0.90. The vertical stress is greater than the horizontal stress, which belongs to the tensile stress area. The side pressure coefficient in the southwest is greater than 1, which belongs to the compression stress area. The middle belongs to the transitional state zone, as shown in Figure 11. The structural fracture is easier to open in the tension stress area, and the permeability is good. In the compression stress zone, structural fractures are more likely to close, and permeability is low.
5.3 The matching relationship between well production, structural fracture, and in situ stress state

The matching relationship between structural fracture and in situ stress state determines the coal reservoir's permeability (Table 5). There are four kinds of matching relations between the two: (1) The structural fractures are densely developed, and the in situ stress is in the state of tension or transition. As a result, the coal reservoir's permeability is the best, and the production of a coalbed methane well is high. (2) The structural fractures are densely developed, and the in situ stress is in the state of compression. Therefore, although the structural fractures are developed, the compressive stress state leads to the closure of the structural fractures, poor permeability of the coal reservoir, and low production of the coalbed methane wells. (3) In the area where structural fractures are not densely developed, the in situ stress is in the state of tension or transition. Therefore, although the in situ stress is conducive to fracture opening because the natural structural fractures are not developed, the coal reservoir's permeability is low, and the production of the CBM well is low. (4) The structural fractures are not densely developed, and the in situ stress is in the state of compression. As a result, the coal reservoir's permeability is lowest in this situation, and CBM well production is low, as shown in Figure 12.

The first matching relationship is that the developed structural fracture and the in situ stress state is tensile or transition state, the permeability is the best, and the production is high. The CBM wells suitable for this situation are M6, M67, M1-5, M60, M5-3, M69, M47-1, M54-4, M46-5, M12-8, and M12-10, a total of 11 wells. Of the 11 CBM wells, nine wells have an average gas production of 1077-1655 m³/d, with an average of 1390 m³/d. Only 2 Wells
### Table 3: Partial structural fracture mapping data

| Observation point number | Lithology     | Rock thickness/cm | The first group of structural fracture | The second group of structural fracture |
|--------------------------|---------------|-------------------|----------------------------------------|----------------------------------------|
|                          |               |                   | Occurrence | Linear density/number/m | Occurrence | Linear density/number/m |
| M001 Siltstone           | 40            | 38∠80             | 3          | 305∠80                  | 2          |
| M002 Siltstone           | 50            | 110∠75            | 4          | 340∠85                  | 1          |
| M003 Siltstone           | 140           | 110∠88            | 6          | 40∠83                   | 6          |
| M004 Fine sandstone      | 150           | 47∠84             | 5          | 332∠66                  | 5          |
| M005 Siltstone           | 30            | 83∠79             | 7          | 343∠74                  | 5          |
| M006 Siltstone           | 235           | 58∠90             | 5          | 324∠79                  | 2          |
| M007 Fine sandstone      | 60            | 280∠59            | 2          | 22∠79                   | 4          |
| M008 Fine sandstone      | 167           | 74∠81             | 3          | 32∠81                   | 1          |
| M009 Fine sandstone      | 150           | 138∠78            | 3          | 26∠84                   | 1          |
| M010 Fine sandstone      | 97            | 17∠76             | 4          | 266∠73                  | 3          |
| M011 Fine sandstone      | 70            | 358∠71            | 2          | 294∠73                  | 3          |
| M012 Fine sandstone      | 90            | 45∠84             | 2          | 133∠73                  | 1          |
| M013 Mudstone            | 50            | 179∠80            | 2          | 95∠82                   | 3          |
| M014 Fine sandstone      | 210           | 99∠80             | 1          | 359∠73                  | 1          |
| M015 Fine sandstone      | 162           | 141∠78            | 2          | 79∠62                   | 2          |
| M016 Fine sandstone      | 140           | 171∠80            | 5          | 70∠83                   | 3          |
| M017 Fine sandstone      | 97            | 331∠68            | 2          | 63∠55                   | 3          |
| M018 Fine sandstone      | 43            | 161∠84            | 6          | 88∠86                   | 3          |
| M019 Fine sandstone      | 135           | 132∠75            | 3          | 213∠69                  | 5          |
| M020 Fine sandstone      | 140           | 150∠89            | 6          | 59∠64                   | 4          |
| M021 Fine sandstone      | 125           | 277∠71            | 5          | 223∠85                  | 2          |
| M022 Fine sandstone      | 60            | 38∠78             | 3          | 132∠84                  | 4          |
| M023 Fine sandstone      | 23            | 40∠88             | 3          | 117∠87                  | 3          |
| M024 Siltstone           | 205           | 90∠85             | 3          | 341∠73                  | 1          |
| M025 Siltstone           | 43            | 141∠82            | 4          | 228∠76                  | 2          |
| M026 Siltstone           | 81            | 213∠80            | 1          | 308∠67                  | 1          |

**Figure 9** Rose diagram of the strike of structural fractures in the study area. (A) Eastern study area; (B) Middle of the study area; (C) Western study area; (D) Entire study area.
produced less than 1000 m$^3$/d, which did not meet the standard for high-yield Wells. The matching accuracy for high-yield Wells was 82%.

The second matching relationship is the development of structural fractures, but the in situ stress state is compression state, the permeability of coal reservoir is low, and the production of CBM well is low. The CBM well suitable for this match is the M57 well. The CBM well is located in a structural fracture zone, but it is also under in situ stress compression, so the production is low. The well's average daily production was only 411 m$^3$/d, making it a low-producing well. The accuracy of this matching relationship with CBM well production is 100%. It is important to note that only one well in the block matches this relationship, and the accuracy may be reduced if there are many CBM wells.

The third matching relationship is that the structural fractures are not developed, but the in situ stress is extensional or transitional. In this case, the coal reservoir’s permeability is generally not too high, and the production of the CBM well is low. The CBM wells that meet this matching relationship are M58, M59, M61-4, M66, M71, and M72, a total of 6 CBM wells. The average daily gas production from the six CBM wells is 158 m$^3$/d. Thus, this matching relationship is accurate in predicting low-producing wells. However, as the number of producing wells increases, accuracy may decrease.

**FIGURE 10** Tectonic fracture development zone in the study area

**TABLE 4** Results of the injection/falloff well test parameters

| Well | $H$ (m) | $P_r$ (MPa) | $P_c$ (MPa) | $P_f$ (MPa) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\sigma_v$ (MPa) | $\lambda$ |
|------|---------|-------------|-------------|-------------|----------------|----------------|----------------|--------|
| M5-3 | 1019.0  | 8.31        | 14.83       | 16.53       | 14.83          | 20.32          | 25.48          | 0.69   |
| M6   | 1130.0  | 11.95       | 19.81       | 20.09       | 19.81          | 28.06          | 28.25          | 0.85   |
| M60  | 1388.5  | 20.50       | 19.79       | 21.31       | 19.79          | 18.23          | 34.71          | 0.55   |
| M27  | 1195.0  | 14.12       | 29.55       | 26.89       | 29.55          | 48.32          | 29.88          | 1.30   |
| M57  | 1116.0  | 11.51       | 29.6        | 30.76       | 29.6           | 47.20          | 27.90          | 1.38   |
| M58  | 1234.0  | 15.40       | 35.58       | 36.53       | 35.58          | 55.48          | 30.85          | 1.48   |
| M59  | 1274.0  | 16.74       | 18.44       | 20.01       | 18.44          | 19.24          | 31.86          | 0.59   |
| M66  | 984.0   | 7.15        | 18.9        | 20.45       | 18.9           | 29.76          | 24.60          | 0.99   |
| M67  | 1073.0  | 10.09       | 18.98       | 20.53       | 18.98          | 26.99          | 26.83          | 0.86   |

Note: $H$ = burial depth; $P_r$ = reservoir pressure; $P_c$ = closing pressure; $P_f$ = fracturing pressure; $\sigma_h$ = minimum horizontal principal stress; $\sigma_H$ = maximum horizontal principal stress; $\sigma_v$ = vertical principal stress; $\lambda$ = lateral stress coefficient.
FIGURE 11 Contour map of side pressure coefficient in the study area

TABLE 5 The matching relationship between CBM well production, structural fracture, and in situ stress state

| Well name | Average gas rate (m³/d) | Production types | Structural fracture | In situ stress state | Matching relationship |
|-----------|-------------------------|------------------|---------------------|---------------------|----------------------|
| M27       | 137                     | Low              | Not dense           | Compression zone    | Bad                  |
| M58       | 67.79                   | Low              | Not dense           | Tension zone        | Bad                  |
| M5-3      | 1402                    | High             | dense               | Tension zone        | Good                 |
| M1-5      | 1358                    | High             | dense               | Tension zone        | Good                 |
| M12-8     | 1655.48                 | High             | dense               | Tension zone        | Good                 |
| M57       | 411.38                  | Low              | Not dense           | Compression zone    | Bad                  |
| M12-10    | 1447.3                  | High             | dense               | Tension zone        | Good                 |
| M47-1     | 1587                    | High             | dense               | Transition zone     | Good                 |
| M54-4     | 382                     | Low              | dense               | Tension zone        | Good                 |
| M59       | 46                      | Low              | Not dense           | Tension zone        | Bad                  |
| M60       | 1195.35                 | High             | dense               | Tension zone        | Good                 |
| M6        | 1450.32                 | High             | dense               | Tension zone        | Good                 |
| M61-4     | 425                     | Low              | Not dense           | Tension zone        | Bad                  |
| M66       | 120.24                  | Low              | Not dense           | Transition zone     | Bad                  |
| M67       | 1077.32                 | High             | dense               | Transition zone     | Good                 |
| M46-5     | 539                     | Low              | dense               | Transition zone     | Good                 |
| M69       | 1342.85                 | High             | dense               | Transition zone     | Good                 |
| M71       | 294.68                  | Low              | Not dense           | Tension zone        | Bad                  |
| M72       | 0                       | Low              | Not dense           | Tension zone        | Bad                  |
The fourth matching relationship is unfavorable; the structural fracture is not developed, and the in situ stress state is compression. In this case, the coal reservoir’s permeability is lowest, and CBM well production is low. The CBM wells that meet this situation are the M27 well.

The correlation between the matching relationship and gas production in 19 wells was analyzed, and it is found that the average daily gas production is high with the first matching relationship. In contrast, the average daily gas production is low in other matching relations. The matching was accurate 89%. It is proved that high-precision structural fracture mapping technology and in situ stress testing technology effectively in the Mabidong block. We use these two technologies to match the characteristics of structural fracture development and in situ stress state. It is found that the development characteristics of structural fractures and the attributes of in situ stress state are the control factors for the comprehensive control of the production of coalbed gas wells in the study area. Therefore, the features of structural fracture development and in situ stress state are the combined control factors of CBM well production.

6 | CONCLUSION

Mabidong block by comprehensive analysis of CBM geological conditions and the relationship between the CBM well production using high-precision structural fracture mapping technology and in situ stress testing technology obtain the structural fracture characteristics and in situ stress state characteristics parameters. Furthermore, the combination characteristics and matching relations were systematically studied, get the following conclusion:

1. Through the study of coal seam depth, thickness, reservoir pressure, the ratio of critical desorption pressure to reservoir pressure, and gas content, it is found that these general parameters have no apparent relationship with the production.
2. The data of 107 observation points were obtained by using high-precision structural fracture mapping technology. It was found that the dominant direction of structural fractures in the study area was NE, followed by NW. According to the density characteristics of structural fractures, four structural fracture zones are divided.
3. According to the in situ stress testing technique, the study area is divided into in situ stress tension state, in situ stress transition state, and in situ stress compression state areas.
4. Based on structural fracture development and in situ stress state characteristics, four kinds of matching relationships are found: ① Structural fracture development and in situ stress state is tension or transition
state zone. ② The structural fractures are developed, but the in situ stress is in the state of compression. ③ The structural fracture is not developed, and the in situ stress is tension or transition zone. ④ The structural fractures are not developed, and the in situ stress is in the compression state.

5. Through the comprehensive analysis of the 19 CBM well production, it is found that the CBM well production is high when the structural fracture dense area and the in situ stress tension and transition area coincide, while the CBM well production is low when other matching relationships. Furthermore, the matching relationship's accuracy in controlling the CBM well production is 89% in the study area. Thus, the characteristics of structural fracture development and in situ stress state are the comprehensive control factors.

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