Analysis of hydraulic fracture behavior and well pattern optimization in anisotropic coal reservoirs

Yulong Liu¹,², Dazhen Tang³, Hao Xu³, Wei Hou⁴ and Xia Yan⁴

Abstract
Macrolithotypes control the pore-fracture distribution heterogeneity in coal, which impacts stimulation via hydrofracturing and coalbed methane (CBM) production in the reservoir. Here, the hydraulic fracture was evaluated using the microseismic signal behavior for each macrolithotype with microfracture imaging technology, and the impact of the macrolithotype on hydraulic fracture initiation and propagation was investigated systematically. The result showed that the propagation types of hydraulic fractures are controlled by the macrolithotype. Due to the well-developed natural fracture network, the fracture in the bright coal is more likely to form the “complex fracture network”, and the “simple” case often happens in the dull coal. The hydraulic fracture differences are likely to impact the permeability pathways and the well productivity appears to vary when developing different coal macrolithotypes. Thus, considering the difference of hydraulic fracture and permeability, the CBM productivity characteristics controlled by coal petrology were simulated by numerical simulation software, and the rationality of well pattern optimization factors for each coal macrolithotype was demonstrated. The results showed the square well pattern is more suitable for dull coal and semi-dull coal with undeveloped natural fractures, while diamond and rectangular well pattern is more suitable for semi-bright coal and bright coal with more developed natural fractures and more complex fracturing fracture network; the optimum wells spacing of bright coal and semi-bright coal is 300 m and 250 m, while that of semi-dull coal and dull coal is just 200 m.

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Keywords
Coalbed methane, coal macrolithotypes, hydraulic fracture, well pattern optimization, Hancheng mining area

Introduction
During the production, the optimal arrangement and post-adjustment of the well pattern are crucial to the efficient development of CBM resources (Crosdale et al., 1998; Li, 2005; Zhang and Liu, 2008). The adaptability of well pattern arrangement should be considered first and the adaptability between well pattern and coal reservoir is conducive to the rapid realization of interwell interference between wells and expand the range of depressurization (Day et al., 2008; Ely et al., 1990; Feng, 2008). Compared with conventional reservoirs, coal have a unique cleat system, and the density and continuity of cleats are key factors in controlling the permeability of coal reservoirs (Liu et al., 2018a; Lyu et al., 2019; Pan et al., 2010; Shi et al., 2019; Zhao et al., 2016). The researches show that the reservoir with a higher density and better continuity of cleats has greater permeability (Handin et al., 1963; Huang et al., 2018). Therefore, the differential development of cleats in the reservoir will lead to the heterogeneity of permeability (Wei and Zhang, 2010; Wu et al., 2017; Zheng et al., 2018). Meanwhile, the difference in the development of the butt and face cleat is also an important factor leading to permeability anisotropy (Crank, 1995; Liu et al., 2016; Tang et al., 2010). The triaxial permeability of coal reservoir shows that there is a significant difference in permeability between different cleat directions in both high and medium rank coal, and the ratio of permeability in face cleat and butt cleat is generally 3:1~10:1 (Cleary et al., 1983; Gan et al., 1972; Tao et al., 2012). For coal reservoirs, the vertical well fracturing is usually used to form artificial fractures for effective mining (Harpalani and Schraufnagel, 1990; Li et al., 2009; Tan et al., 2017; Zhang et al., 2016). The more cleavage system developed in the reservoir, the more obvious the anisotropy of reservoir. When fracturing the heterogeneous reservoir, the artificial fracture is easier to communicate with natural fracture system, forming crisscross fracture network and improving the reservoir permeability (Blanton, 1982; Fan et al., 2014; Jeffrey et al., 2009; Liu et al., 2019; Valko and Economides, 1994). Therefore, when formulating a CBM well network deployment plan, the well network arrangement should be carried out based on the degree of permeability coal anisotropy as combined with the distribution of artificial fractures (Agarwal et al., 1998; Chaianansutcharit et al., 2001; Salehi and Nygaard, 2015; Xu et al., 2014).

The gas in coal reservoirs is mainly seepage in the natural fracture system, and the hydraulic fracturing has the function of communicating the cleavage systems, and modifying the reservoir permeability (Adachi et al., 2007; Li et al., 2009; Tan et al., 2017). The researchers determined that the geometry of fractures is complicated and the initiation and propagation behaviors are mainly controlled by the cleavage system (Beugelsdijk et al., 2000; Close, 1993; Dean and Schmidt, 2009; Liu et al., 2019). The CT tomographic scans show that the bright coal has the most developed pore-fracture system, and only a few filamentous micron-scale cracks develop in dull coal. Meanwhile, visible fracture systems that including exogenetic fractures, gas-expanding fractures, and cleats are also distribution diversity from the coal macrolithotype (Lyu et al., 2020; Zhao et al., 2019). Field tests and
laboratory-scale experiments have shown that, the bright and semi-bright coals generally
developed multigroup of open and shear gas-expanding fractures with large length-width
ratio and good connectivity. The semi-dull coal could be found several isolated open frac-
tures. To the dull coal, there are few exo-fractures and if the view is magnified further (Zhao
et al., 2017). Compared to the exo-microfracture, the cleats occur almost exclusively in
bright coal and semi bright coal, which usually do not develop in semi-dull and dull coal
because the certain macerals usually have an important influence on the endo-microfracture
formation at the stage of coalification (Chalmers and Bustin, 2007; Zhao et al., 2016). Due
to the influence of coal reservoir heterogeneity, there are obvious differences in the propaga-
tion rules of hydraulic fractures in all aspects, resulting in strong anisotropy of perme-
ability, and affects the determination of the well pattern and spacing (Diamond and Øyler,
1987; Jeffrey et al., 2009; Xu et al., 2014; Zhang and Liu, 2008). Thus, when developing the
coal reservoirs, the completion technologies and production measures should adapt to dif-
f erent types of coal reservoirs, the adjustment and optimization of the pre-production and
post-well wells should also be tailored to local conditions (Karacan and Mitchell, 2003; Li
et al., 2017; Pan et al., 2014). However, the well network optimization and adjustment
researches traditionally disregard this diversity imparted by the coal petrology, and there
is currently no quantitative research system. Therefore, clarifying the orientation and geome-
try of fractures formed by fracturing, analyzing the fracture propagation of hydraulic
fractures in different coal macrolithotypes, and carrying out development plans under
local conditions are of great significance for the refined development of CBM resources.

In this work, the geometry behavior of hydraulic fracture was evaluated for each macro-
lithotype with microseismic monitoring technology, and the impact of the macrolithotype
on hydraulic fracture initiation and propagation was investigated systematically.
Furthermore, based on the characteristics of hydraulic fracture under the control of coal
petrology, the relationship between well pattern, well pattern density and different coal
macrolithotypes were analyzed according to the characteristics of gas pressure transmission
in different coal macrolithotype, and the model of well pattern optimization and adjustment
under the control of coal petrology was established.

**Methods**

**Microseismic monitoring model**

To capture the fracturing fractures orientation and geometric size of coal reservoir, micro-
seism monitoring of wells that located on the eastern margin of the Ordos Basin in the
Shaanxi province, China (Figure 1) were carried out by PetroChina Eastern Geophysics
Company. On this basis, the relationship between fracture complexity and gas well produc-
tivity was analyzed by combining field capacity data.

**Wells information and platform deployment**

To capture the characteristics of fracturing fractures in different coal macrolithotypes, the
CNPC company selected fracturing wells with similar burial depth and in-situ stress for
microseismic monitoring. Before fracturing, geophones were installed within 2 km around
the well, and microseismic signals generated by fracturing were monitored and collected on
the ground, and observation data were processed and analyzed using micro-fracture imaging
technology. For the layout principle of the seismic network: (1) surrounding the projected points on the fracturing section, covering the target area uniformly and randomly; (2) minimizing background noise, that is, avoiding fracturing car groups, personnel vehicles, high-voltage lines, production wells, etc.; (3) ensure that the instrument can work reliably and continuously under the permitted environmental conditions; 13 seismometers were deployed at points around the monitoring well.

**Fracture energy scanning**

Before implementing vector scan superposition, the seismic wave velocity model of the well area must be obtained, which is the basis for the application of scanning technology. Based on the existing sonic logging data of the well, the exploration experience data of the surface loess layer, and the characteristics of the local surface topography, the 909.7 m altitude of HC-01 is defined as the 0-point vertical depth of the scanning model. The topographic map used for the created velocity model and the P-wave velocity model is shown in Figures 2 and 3.

P-wave velocity is obtained by sonic logging. Since the large amplitude of S-wave, the fracture is likely controlled by the tectonic principal stress field after it is slightly away from the well site, and the S-wave velocity model is used. After forming the P-wave model, divide by 1.732 to obtain the S-wave velocity model (Figure 3).

Based on the velocity model, a coarser grid, and a time interval of 100 m and 10 minutes were used to calculate the fracture scans, and the approximate range of the main fracture was estimated. Then, the finer grids and time intervals of 12.5 m and 2.5 minutes were used
to scan the higher energy periods. Based on this, the temporal and spatial distribution of fracturing fractures was described, analyzed, and explained. In this calculation process, the data recording per unit time is not counted as data preprocessing, and it takes about 4–20 times the CPU time.

Figure 2. The topographic map used for the created velocity model.

Figure 3. The model used for the used for P-waves.
Well pattern optimization method

For coal reservoirs, vertical well fracturing to form artificial fractures is currently used for effective mining. In general, the more developed of the cleaving system, the more obvious the anisotropy of the permeability (Li et al., 2012). When fracturing this heterogeneous reservoir, the artificial fracture is easier to communicate with the natural fracture system, forming a crisscross fracture network. Thus, for considering the influence of coal macro-lithotype on reservoir anisotropy ($K_X/K_Y$), the method of well pattern optimization that under the control of coal petrology is proposed by the Eclipse numerical simulation software.

Based on the production data, the influence of different well patterns (including diamond-shaped, square-shaped and rectangular-shaped well pattern) on the gas production that under different permeability anisotropy levels ($K_X=K_Y$, $K_X=5K_Y$, $K_X=10K_Y$ and $K_X=15K_Y$) was simulated by numerical simulation software (Figure 4).

To capture the impact of natural fractures on the well pattern optimization in anisotropic coal reservoirs, the natural fractures according to the micro-resistivity scanning logging are set in the different coal macrolithotypes. The natural fracture density in bright coal and semi-bright coal is 24/10 cm and 18/10 cm, while that of semi-dull coal and dull coal is just 5/10 cm and 3/10 cm. The natural fractures in the model are mainly gas-expanding fractures and cleats, and the length is in the range of 1 cm $\sim$ 1 m. Additionally, combined with the characteristics of coal reservoirs in Hancheng area, the buried depth and thickness of coal seams were selected as numerical simulation parameters, and the wells were analyzed by COMET3 numerical simulation software. By fitting the 10-year cumulative production of wells, the geological parameters were corrected (Table 1). Figure 5 shows the fitting curve of gas production history of well HC-01. Through continuous adjustment of parameters for historical fitting, the productivity prediction model under the current well pattern and development conditions was obtained. From the results, the fitting degree is high, which meets the accuracy requirements.

Results and discussion

The impact of macrolithotype on hydraulic fracture

The 2/3D distribution with periods of higher fracture energy is integrated and listed in Figure 6. Based on this, the spatial distribution of the main fracture is analyzed. Field logging data show that the HC-01 is dominated by the bright coal, when fracturing this reservoir, the hydraulic fracturing can modify the cleat system that widely developed in bright coal, hydraulic fracturing and dendritic crack are easier to propagate in all directions, and the artificial fractures with the cleats and structural fractures are easily form a “complex fracture network” (Liu et al., 2018b).

The semi-dull and dull coals have fewer fractures, and which with serious mineral filling phenomena (Zhao et al., 2017). Therefore, it is hard to connect the cleat system and contribute to a transverse fractures network structure that centered on hydraulic fractures. On the other hand, compared with bright coal, the elastic modulus of dull coal is larger (Liu al et al., 2018b), and the fracturing fractures are easy to form long and narrow fractures, and it is difficult to form a larger fracturing scale (Figure 7).
The microseismic monitoring results show that the hydraulic fracture in HC-02 well is mainly isolated, with a length of 172 m. Compare with the well of HC-02, the HC-01 well is mainly composed of reticular fractures as the fractures can communicate with the natural fractures near the wellbore. The range of fracturing in HC-01 well is wide, but the length of the main fracture is only 97.5 m (Table 2). By analyzing the productivity data of the two wells, it is found that the HC-01 well with better gas production. The highest daily gas production is 2300 m$^3$/d, and the accumulated gas is $800\times10^4$ m$^3$. Although the main fracture length of HC-02 well is higher, the daily and cumulative gas production of gas wells is

![Figure 4. Numerical model of different well pattern.](image)

**Table 1.** Main parameters required for geological model.

| Basic parameters                 | Value | Basic parameters                | Value |
|----------------------------------|-------|---------------------------------|-------|
| Burial depth/m                   | 978   | Gas deviation factor            | 0.9   |
| Coal thickness/m                 | 8.4   | Gas volume factor/m$^3$/m$^3$    | 0.01  |
| Reservoir pressure/Mpa           | 11.3  | Viscosity coefficient/Pa-s      | 0.00001|
| Minimum horizontal principal stress/Mpa | 17.77 | Ideal gas constant/Pa.m$^3$     | 8.314 |
| Maximum horizontal principal stress/Mpa | 26.92 | Average permeability/mD        | 2.34  |
| Vertical stress/Mpa              | 24.52 | Average porosity/%             | 8     |

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Figure 5. Fitting curve of gas production history of well HC-01.

Figure 6. The geometry of hydraulic fracturing in HC-01 well using microseismic monitoring.

Figure 7. The geometry of hydraulic fracturing in HC-02 well using microseismic monitoring.
only 750 m$^3$/d and 430×10$^4$ m$^3$, indicating that the complexity of fracturing fracture has a greater impact on the productivity characteristics of gas wells.

This result seems to be contrary to the previous conclusions, but in fact, leading to such results mainly due to the characteristics of coal reservoirs. Although the propagation of the main fracture in the bright coal is short, the fracture can communicate with the cleavages and natural fractures, leading to the formation of fracture networks around the main fracture. The permeability of this area is improved, which is conducive to the permeability of the area and enhance the flow velocity, facilitating the formation of area pressure drop. Owing to the tight reservoir, the fracture network of dull coal is mainly an isolated distribution, and the permeability near the main fracture does not change much. Since there are few branch fractures, the pressure drops of gas wells appear mainly as flat ellipsis, and it is difficult to form an effective pressure drop of a large area near the circle (Figure 8).

The underground excavation and observation of fracturing wells in Hancheng mining area show that the distribution range of the proppant injected is generally 25–40 m near the wellbore (Wu, 2010). This illustrates the effective fracturing reconstruction of the gas well is limited to about 25–40 m near the wellbore at present, and the excessively long fracturing fractures have little significance for increasing the scope of transformation. However, the formation of long fractures to expose more coal seams is still the main goal of coal fracturing (Fan et al., 2014; Jeffrey et al., 2009). If network fractures are to be formed to increase the production of single wells, it is necessary to continue to increase the scale of fracturing and the network fractures on the current basis (Beugelsdijk et al., 2000; Dean and Schmidt, 2009).

### Table 2. The fracture distribution by microseismic monitoring.

| Fracture parameter | HC-01 Depth (951.50~957.10) | HC-02 Depth (782.0~785.5) |
|--------------------|-----------------------------|---------------------------|
| Fracture length/m  |                             |                           |
| East wing          | 43.7                        | 67.2                      |
| West wing          | 53.8                        | 105.4                     |
| Full length of fracture | 97.5                      | 172.6                     |
| Fracture Height/m  | 959.1~965.5 (6.4)           | 779.2~788.9 (9.7)         |
| Fracture azimuth/° | North East 70.5°             | North East 55.4°          |

### Figure 8. The relationship between fracturing fractures and drainage area of coal macrolithotypes.
Macrolithotypes impart a fracture distribution, which further impacts the hydrofracture stimulation and subsequent discharge radius and coalbed methane production. As the fracture conductivity of the fracture is the same, the drainage radius of the gas well will gradually increase with the length of the main fracture. In the actual fracturing of gas wells, the complexity of fractures often determines the productivity characteristics of gas wells. Generally, the more developed the reservoir fractures, the easier it is to form mesh fractures after fracturing, thereby increasing the corresponding drainage radius and improving the capacity.

**Well pattern characteristics controlled by coal petrology**

*Research on optimization method of well pattern.* Figure 9 is the recovery degree curves under the different well pattern types. As the reservoir with lower heterogeneity, the production of square-shaped is the highest, the rectangular-shaped is lowest and followed by the diamond-shaped well pattern. However, as the permeability anisotropy increases, the difference in recovering efficiency of the three well patterns gradually decreases. When the permeability anisotropy is $K_X = 10K_Y$, the recovery efficiency of the square well pattern is slightly higher than that of the diamond-shaped and rectangular-shaped at the initial stage of productivity. However, with the drainage proceeding, the recovery degree of the diamond-shaped is the highest, followed by the rectangular-shaped, and the square-shaped is the lowest. As the degree of reservoir anisotropy is $K_X = 15K_Y$, the rectangular-shaped is obviously higher than the diamond-shaped and the square-shaped well pattern.

*Optimized deployment of well pattern.* Affected by the cleats and propagation of fracturing fractures, the permeability of coal reservoirs in different directions is anisotropic, resulting in higher propagation velocity of pressure in the high permeability zone than the low (Jeffrey et al., 2009; Zhang and Liu, 2008). In order to achieve the goal of balancing depressurization and optimizing CBM production, well spacing can be increased in the direction of higher...
permeability, while it should be reduced appropriately in the direction of lower permeability (Zhang and Liu, 2008). In the design of diamond-shaped and rectangular-shaped well pattern, they were required to deploy them in the form of different well spacing according to permeability orientation (Zuber and Kuuskr, 1990; Zulkarnain, 2005). Therefore, these types are more suitable for coal with high permeability anisotropy. The square-shaped is suitable for reservoirs with a weak cleat system and heterogeneity (Figure 10). These reservoir permeabilities are almost indistinguishable in the plane and vertical, and the pressure propagates almost equally across the coal seam during drainage and depressurization.

Thus, the square-shaped is more suitable for the dull and semi-dull coal in which the natural fractures are not developed or underdeveloped. For this, is not only can take the advantage of its early gas production speed but also help optimize well pattern deployment and improve development results (Figure 10). Compared with the square-shaped, the well pattern of diamond-shaped is more suitable for the semi-bright coal and bright coal reservoirs that with more complex natural fractures and fracturing fracture network (Figure 11). In addition, the results show that the rectangular-shaped in bright coal reservoirs with well-developed natural fractures and strong reservoir permeability is most conducive to improving the adaptability of well pattern and improving gas production.

**Density optimization of CBM well pattern**

The results show that the square well pattern is more suitable for dull coal and semi-dull coal with undeveloped natural fractures, while the diamond and rectangular well pattern is more suitable for semi-bright coal and bright coal with more developed natural fractures and more complex fracturing fracture network. Thus, 102 single-well geological models with different well patterns and well spacings under different coal macrolithotype were established. Combined with the actual well spacing of the mine, 18 well spacing schemes were designed, as showed in Table 3.

Based on the history fitting, COMET3 software was used to optimize the productivity indexes of the above 18 schemes (Table 3). The result demonstrates that the recovery degree increases with the density of well pattern, whether it is bright, semi-bright, or semi-dull and dull coal (Figure 12). However, as the spacing is too small, the interwell interference will form earlier, and the gas production peak will form accordingly and resulting in the stable

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**Figure 10.** Diagram of fracture system and well pattern deployment in dull coal.
Figure 11. Diagram of fracture system and well pattern deployment in bright and semi-bright coal.

Table 3. Result of numerical simulation optimization index for coalbed methane.

| Coal macrolithotype | Scheme | Well pattern | Peak time (Y) | Peak gas production (m³/d) | Stable production time (Y) | Recovery ratio (%) |
|---------------------|--------|--------------|---------------|-----------------------------|------------------------------|-------------------|
| Bright coal         | 1      | Rectangular 200*250 | 3             | 2200                        | 4.1                          | 42.05             |
|                     | 2      | Rectangular 250*300 | 4.8           | 2140                        | 5.9                          | 40.75             |
|                     | 3      | Rectangular 300*350 | 5.8           | 1900                        | 6.6                          | 34.15             |
|                     | 4      | Rectangular 350*400 | 7.8           | 1800                        | 8                            | 26.37             |
| Semi-bright coal    | 5      | Diamond 200*200   | 2.2           | 2000                        | 3.1                          | 39.13             |
|                     | 6      | Diamond 250*250   | 3.7           | 1900                        | 5.3                          | 36.26             |
|                     | 7      | Diamond 300*300   | 4.3           | 1730                        | 5.9                          | 30.67             |
|                     | 8      | Diamond 350*350   | 5.2           | 1600                        | 6.3                          | 28.42             |
| Semi-dull coal      | 9      | Square-shaped 150*150 | 1.8          | 1600                        | 3                            | 33.36             |
|                     | 10     | Square-shaped 200*200 | 2.7          | 1480                        | 4.2                          | 31.21             |
|                     | 11     | Square-shaped 250*250 | 3.1          | 1100                        | 4.8                          | 27.18             |
|                     | 12     | Square-shaped 300*300 | 3.4          | 880                         | 5.3                          | 24.64             |
|                     | 13     | Square-shaped 400*400 | 5.8          | 600                         | 6.5                          | 20.51             |
| Dull coal           | 14     | Square-shaped 150*150 | 1.7          | 1450                        | 2.8                          | 29.38             |
|                     | 15     | Square-shaped 200*200 | 2.5          | 1400                        | 4.1                          | 27.33             |
|                     | 16     | Square-shaped 250*250 | 3             | 960                         | 4.5                          | 24.26             |
|                     | 17     | Square-shaped 300*300 | 3.2          | 800                         | 5.3                          | 22.17             |
|                     | 18     | Square-shaped 400*400 | 5.5          | 550                         | 6.6                          | 17.66             |
production and high production time shorter. However, as the well spacing increases, it is difficult to form the well interference, and the gas production peak period is difficult to reach.

The ideal capacity trend can be formed only when the compatibility between well spacing density and reservoir is well (Zulkarnain, 2005). That is, after 2 to 4 years of production, pressure drop superimposition can be formed. Therefore, comparing the cumulative gas production, stable production time, recovery degree and peak time of single well in different coal macrolithotype, and the optimum wells spacing of bright coal and semi-bright coal is 350/km² and 250/km², while that of semi-dull coal and dull coal is 200/km².

**Optimization and adjustment of well pattern**

To quantitatively evaluate the effect of well pattern adjustment and development index of reservoir, the pilot test area was selected to optimize well pattern spacing in the study area. Meanwhile, based on the numerical simulation technology, the pressure drop effect and production index after well pattern adjustment were evaluated quantitatively.

**Comprehensive evaluation of well pattern infill feasibility.** The original development plan of Hancheng is to deploy a set of diamond-shaped wells in the reservoirs with good reservoir properties and high gas content, and the average well spacing is about 300 m. However, due to the strong heterogeneity of coal reservoirs, well pattern arrangement in a single form is less adaptable to some coal macrolithotype reservoirs. Besides, non-uniform well spacing is adopted in the development process according to reservoir physical properties and gas-bearing. Up to now, the basic pattern in the Hancheng is dominated by the irregular well pattern, and most of the wells are concentrated in the superiority reservoirs such as bright and semi-bright coal. In bright coal reservoir, the well spacing is 12.5/km², and the average well spacing is 275 m. The well density in the semi-bright coal is 10.65/km², and the average well spacing is 300 m. The well density in the semi-dull coal and dull coal is 200/km².
well spacing is 305 m. The density of semi-dull coal and dull coal wells is 9.84~8.51/km², and the well spacing is 313 m~341 m (Table 4).

According to the existing well pattern, the reserves utility of bright coal is relatively high, and the drainage radius superposition is larger than the average well spacing, indicating that the interwell interference has been formed, and there is little room for infilling the well pattern. For the dull and semi-dull coal, the current average well spacing has approached or exceeded the economic and technical limits, but due to the poor reservoir properties, the interwell interference has not yet been realized. Thus, considering the economic factors, the types of these reservoirs do not have the economic conditions of well pattern infilling under the current gas price and production technology. Therefore, comparing the relationship between the gas drainage radius and the limit values of economy and technology, the study area has lost the condition of integral infilling, and the semi-bright coal may still have infilling potential.

**Optimal adjustment scheme of well pattern.** Hancheng branch has deployed four infill wells in the Han 3 well group with semi-bright coal as the main production layer in recent years. The distribution of infill wells is shown in Figure 13. The Han 3 well group has deployed 28 production wells, the well spacing of which 16 are greater than 300 m, 12 are less than 300 m, and the minimum is 251 m; the density of the well pattern after encryption is 7.3/km² to 8.65/km². The well spacing is also reduced from 358 m to 275 m. After infilling adjustment, the well pattern of the pilot test area is gradually improved.

Combining the economic and technical limits well spacing, numerical simulation of infilled Han 3 well group is carried out. On the basis of historical fitting, the pressure drop effect and productivity characteristics of the infilled reservoir is predicted respectively. From the pressure distribution of Han 3 test well group, the production of old wells is greatly affected after infilling. The areas with obvious pressure reduction are concentrated around the wells of Han 3–2, Han 3–3, Han 3–5, and Han 3–7, and the effect of pressure reduction in the infilling area is obvious (Figure 14).

Before infilling, the diamond-shaped well pattern has been formed in the test well group. However, due to the late commissioning time of the diamond-shaped, the interwell interference has not yet been formed. For example, 8 wells centered on the Han 3–1 well are Han 3–1 well, Han 3–2 well, Han 3–3 well, Han 3–4 well, Han 3–5 well, Han 3–7, Han 3–8 well and Han 3–9 well. Among them, except well Han 3–8, because of its large fluid production, the gas production is low, the daily production of other wells is around 800–1000 m³. The cumulative gas production of well Han3–1 is stable before infilling. However, since four infilling wells put into operation, the cumulative gas production of well Han 3–1 increases linearly, and the other 7 wells show the same trend (Figure 15). The actual drainage and

| Reservoir      | Well spacing density (km²) | Average well spacing (m) | Average drainage radius (m) |
|---------------|-----------------------------|--------------------------|-----------------------------|
| Bright coal   | 12.5                        | 275                      | 166                         |
| Semi-bright coal | 10.65                      | 305                      | 113                         |
| Semi-dull coal | 9.84                       | 313                      | 86                          |
| Dull coal     | 8.51                        | 341                      | 57                          |

Table 4. Statistics of average well spacing corresponding to coal macrolithotype.
production data show that the average daily gas production of 8 wells centered on Well Han 3–1 after infilling is significantly higher than that before infilling, which indicates that there is obvious interwell interference among wells of Han 3 after infilling (Figure 14), and the recoverable reserves of reservoirs are further utilized.

**Figure 13.** Distribution of well pattern encryption for Han 3 in Hancheng mining area.

**Figure 14.** Pressure distribution of Han 3 test well group.
Conclusion

- The hydraulic fracture differences will modify the permeability pathways and the well productivity seems to be different when developing different macrolithotype reservoirs. The microseismic monitoring results show that the fractures are controlled by the macrolithotype, and fractures propagate in bright coal also dominated by the complicated fracturing fracture networks as the cleat-systems is widely developed, and the “simple” case often happens in the coal that the dull-lithotype is rich.
- Considering the difference of hydraulic fracture and permeability, the CBM productivity characteristics controlled by coal petrology were simulated. The results show the square-shaped is more suitable for the dull and semi-dull coal, while the diamond-shaped and rectangular-shaped well pattern is more suitable for the semi-bright and bright coal reservoirs that with more complex natural fractures and fracturing fracture network. The spacing of 350 m x 300 m for bright coal is more conducive to realize investment recovery and further rolling development as soon as possible. The optimum wells spacing of semi-bright coal is 250 m, while the semi-dull and dull coal is only 200 m.
- Based on the principle of well-infilling adjustment and deployment, four wells infilling were deployed in Han 3 well group with semi-bright coal as the main production layer. After infilling, Han 3 well group formed obvious inter-well interference and further exploited recoverable reserves. The actual drainage and production data show that the average daily gas production of eight wells centered on Han 3-1 well are significantly higher than before infilling, and the development well pattern in this area became more perfect after infilling adjustment.

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References
Adachi J, Siebrits E, Peirce A, et al. (2007) Computer simulation of hydraulic fractures. International Journal of Rock Mechanics and Mining Science 44(5): 739–757.
Agarwal RG, Gardner DC and Kleinst SW (1998) Analyzing well production data using combined type curve and decline curve analysis concepts. SPE 2: 478–486.
Beugelsdijk L, Pater CJ and Sato K (2000) Experimental hydraulic fracture propagation in a multi-fractured medium. SPE 59419: 25–26.
Blanton TL (1982) An experimental study of interaction between hydraulically induced and pre-existing fractures. SPE 10847: 16–18.
Chaianansutcharit HY, Chen LW and Teufel (2001) Impacts of permeability anisotropy and pressure interference on coalbed methane (CBM) production. SPE 71069: 21–28.
Chalmers GR and Bustin RM (2007) On the effects of petrographic composition on coalbed methane sorption. International Journal of Coal Geology 69: 288–304.
Cleary MP, Crockett AR, Martinez VM, et al. (1983) Surface integral schemes for fluid flow and induced stresses around fractures in underground reservoirs. SPE 11632: 283–294.
Close JC (1993) Natural fractures in coal. In: Law BE and Rice DD (eds) Hydrocarbons from Coal. AAPG Geology 38: 119–132.
Crank J (1995) The Mathematics of Diffusion. 2nd ed. London: Oxford University Press.
Crosdale PJ, Beamish BB and Valix M (1998) Coalbed methane sorption related to coal composition. International Journal of Coal Geology 35: 147–158.
Day SA, Sakurovs R and Weir S (2008) Supercritical gas sorption on moist coals. International Journal of Coal Geology 74: 203–217.
Dean RH and Schmidt JH (2009) Hydraulic-fracture predictions with a fully coupled geomechanical reservoir simulator. SPE 14: 707–714.
Diamond WP and Oyler DC (1987) Effects of Stimulation Treatments on Coalbeds and Surrounding Strata. Evidence from underground observations. Pittsburgh, PA: U.S. Department of the Interior Bureau of Mines Ri.
Ely JW, Zbnowsk R and Zuber MD (1990) How to develop a coalbed methane prospect: A case study of an exploratory five-spot well pattern in the Warrior basin, Alabama. SPE 20666: 487–496.
Fan T, Zhang GQ and Cui JB (2014) The impact of cleats on hydraulic fracture initiation and propagation in coal seams. Petroleum Science 11: 532–539.
Feng P (2008) A discussion on CBM producing well pattern layout method in Luan mining area. Coal Geology China 20(11): 21–23.
Gan H, Nandi SP and Walker PL (1972) Nature of the porosity in American coals. Fuel 51: 272–277.
Handin J, Hager RV and Friedman M (1963) Experimental deformation of sedimentary rocks under confining pressure: Pore pressure tests. *AAPG* 47: 717–755.

Harpalani S and Schraufnagel A (1990) Measurement of parameters impacting methane recovery from coal seams. *International Journal of Mining Geology Engineering* 8: 369–384.

Huang L, Ning Z, Wang Q, et al. (2018) Effect of organic type and moisture on CO$_2$/CH$_4$ competitive adsorption in kerogen with implications for CO$_2$ sequestration and enhanced CH$_4$ recovery. *Applied Energy* 210: 28–43.

Jeffrey RG, Zhang X and Thiercelin MJ (2009) Hydraulic fracture offsetting in naturally fractured reservoirs: Quantifying a long-recognized process. *SPE* 119351: 313–327.

Karacan CO and Mitchell GD (2003) Behavior and effect of different coal microlithotypes during gas transport for carbon dioxide sequestration into coal seams. *International Journal of Coal Geology* 53: 201–217.

Li M (2005) Discussion on recovered percent of coal-bed methane in Zaoyuan well pattern of Qinshui basin. *Acta Petrolei Sinica* 30(1): 91–95.

Li S, Tang D, Xu H, et al. (2012) The pore-fracture system properties of coalbed methane reservoirs in the Panguan Syncline, Guizhou, China. *Geosciences Frontier* 3: 853–862.

Li X, Kang Y and Luo P (2009) The effects of stress on fracture and permeability in coal bed. *Coal Geology & Exploration* 37(1): 29–32.

Li Y, Cao D, Wu P, et al. (2017) Variation in maceral composition and gas content with vitrinite reflectance in bituminous coal of the Eastern Ordos Basin, China. *Journal of Petroleum Science and Engineering* 149: 114–125.

Liu Y, Tang D, Hao X, et al. (2018a) Quantitative characterization of Middle-high ranked coal reservoirs in the Hancheng Block, Eastern margin, Ordos Basin, China: Implications for permeability evolution with the coal macrolithotypes. *Energy Sources Part A* 41: 201–215.

Liu Y, Tang D, Hao X, et al. (2018b) The impact of coal macrolithotype on hydraulic fracture initiation and propagation in coal seams. *Journal of Natural Gas Science and Engineering* 56: 299–314.

Liu Y, Tang D, Xu H, et al. (2016) Study on microscopic pores structure and adsorption characteristics of different lithotypes. *Coal Engineering* 11: 165–169.

Liu Y, Xu H, Tang D, et al. (2019) The impact of coal macrolithotype on reservoir productivity, hydraulic fracture initiation and propagation. *Fuel* 21: 417–483.

Lyu SF, Wang SW, Chen XJ, et al. (2019) Experimental study of a degradable polymer drilling fluid system for coalbed methane well. *Journal of Petroleum Science and Engineering* 178: 678–690.

Lyu SF, Wang SW, Chen XJ, et al. (2020) Natural fractures in soft coal seams and their effect on hydraulic fracture propagation: A field study. *Journal of Petroleum Science and Engineering* 192: 107255.

Pan J, Wang H, Wang K, et al. (2014) Relationship of fractures in coal with lithotype and thickness of coal lithotype. *Geomechanics and Engineering* 6: 613–624.

Pan Z, Connell LD, Camilleri M, et al. (2010) Effects of matrix moisture on gas diffusion and flow in coal. *Fuel* 89: 3207–3217.

Salehi S and Nygaard RJ (2015) Full fluid-solid cohesive finite-element model to simulate near wellbore fractures. *Journal of Energy Resources Technology* 137(1): 012903.1–012903.9.

Shi F, Deng B, Yin G, et al. (2019) Kinetic behavior of heterogeneous sorption deformation on coal: Effect of maceral/micro-lithotype distribution. *International Journal of Coal Geology* 216: 103324.

Tan P, Jin Y, Han K, et al. (2017) Analysis of hydraulic fracture initiation and vertical propagation behavior in laminated shale formation. *Fuel* 206: 482–493.

Tang D, Wang S and Jin Z (2010) *Coal Reservoir Physical Properties Control Mechanism and Favorable Reservoir Prediction Methods*. Beijing: Science Press.

Tao S, Wang YB and Tang DZ (2012) Dynamic variation effects of coal permeability during the coalbed methane development process in the Qinshui Basin, China. *International Journal of Coal Geology* 93: 16–22.
Valko P and Economides MJ (1994) Propagation of hydraulically induced fractures – A continuum damage mechanics approach. *International Journal of Rock Mechanics and Mining* 31(3): 221–229.

Wei Z and Zhang D (2010) Coupled fluid flow and geomechanics for triple-porosity/dual-permeability modeling of coalbed methane recovery. *Journal of Rock Mechanics and Mining Science* 47: 1242–1253.

Wu QH (2010) *Study and Application on the Stimulation Fluid in Hancheng Block of the Eastern Ordos CBM Field*. Beijing: China University of Geosciences.

Wu S, Tang D, Li S, et al. (2017) Effects of geological pressure and temperature on permeability behaviors of middle-low volatile bituminous coals in Eastern Ordos Basin, *China. Journal of Petroleum Science and Engineering* 23: 201–207.

Xu B, Li X and Ren W (2014) Optimization model of well pattern and spacing in CBM reservoir using the concept of balanced depressurization. *Journal of China University of Mining & Technology* 42(1): 88–93.

Zhang J and Liu J (2008) Probe into the optimal design of coal-bed methane well network. *Sci-Tech Information Development & Economy* 18(10): 210–211.

Zhang ZQ, Shi YM, Li H, et al. (2016) Experimental study on the pore structure characteristics of tight sandstone reservoirs in upper Triassic Ordos Basin China. *Energy Exploration & Exploitation* 34(3): 418–439.

Zhao JL, Xu H, Tang D, et al. (2016) Coal seam porosity and fracture heterogeneity of macrolithotypes in the Hancheng block, Eastern margin, Ordos Basin, China. *International Journal of Coal Geology* 159: 18–29.

Zhao JL, Tang D, Qin Y, et al. (2017) Evaluation of fracture system for coal marcolithotypes in the Hancheng block, Eastern margin of the Ordos Basin, China. *Journal of Petroleum and Engineering* 159: 799–809.

Zhao JL, Tang D, Qin Y, et al. (2019) Fractal characterization of pore structure for coal macrolithotypes in the Hancheng area, southeastern Ordos Basin, China. *Journal of Petroleum Science and Engineering* 178: 666–677.

Zheng S, Jun S, Tao S, et al. (2018) The modified gas-water two phase version flowing material balance equation for low permeability cbm reservoirs. *Journal of Petroleum Science and Engineering* 165: 726–735.

Zuber MD and Kuuskr VA (1990) Optimizing well spacing and hydraulic-fracture design for economic recovery of coalbed methane. *SPE* 17726: 98–102.

Zulkarnain (2005) Simulation study of the effect of well spacing, effect of permeability anisotropy, and effect of palmer and Mansoori model on coalbed methane production. *SPE Reservoir Engineering* 10(6): 623–636.