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Research and Application of Treatment Measures for Low-Yield and Low-Efficiency Coalbed Methane Wells in Qinshui Basin

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Abstract: China is rich in high-grade coalbed methane resources, accounting for one-third of the total amount of coalbed methane resources. Qinshui Basin is the main high ranking coalbed methane mining basin in China. In the early stage of CBM development, low-production and low-efficiency wells were formed in the process of block development because of an insufficient understanding of reservoir geological conditions. The existence of low-yield and low-efficiency wells with low output and a poor development benefit seriously restricts the efficient development of coalbed methane. In order to improve the overall development efficiency of coalbed methane fields, how to revitalize low-yield and low-efficiency wells is the main problem facing the development process of coalbed methane. With the deepening understanding of the study area geology, the formation of low-yield and low-efficiency wells has been basically identified. With the advancement of development technology, developers have the ability to retrofit some low-producing and inefficient wells. Low-production and low-efficiency wells are widely distributed. It is difficult to find the criteria for classifying low-producing and low-efficiency wells because of the great differences in geological conditions and reservoir physical properties in different blocks. In addition, the causes of a low-production and low-efficiency well are complex, as the same well is often caused by many reasons, and how to identify the causes of low-production and low-efficiency wells is difficult. In recent decades, developers have studied many methods to retrofit low-production wells, but the retrofit results are not satisfactory. How to choose an economical and efficient reservoir reconstruction method to revitalize low-production and low-efficiency wells is particularly important. This paper starts with the definition of low-production and low-efficiency wells in different blocks, combining an economic evaluation and productivity characteristics to judge whether they are low-production and low-efficiency wells, and defines the distribution of low-production and low-efficiency wells in blocks. The reasons for the formation of low-production and low-efficiency wells are analyzed with the geological characteristics, production dynamic performance, and engineering reconstruction effects. This paper makes a comparative analysis of the current relatively mature low-production and low-efficiency well treatment measures, clearly identifies the advantages and disadvantages of different treatment measures, and takes corresponding stimulation measures for different causes of low-production and low-efficiency wells. The research shows that there are 687 low-production and low-efficiency wells in block A, accounting for 69.4% of the total number of wells, and the low-production and low-efficiency wells account for a relatively large proportion; so, it is necessary to treat them. The main causes of low-production and low-efficiency wells are geology, engineering and drainage systems. The geological reason mainly refers to the low gas production of coalbed methane wells influenced by three factors: resource abundance, faults, and collapse columns. According to the different causes, three treatment measures of large-scale secondary fracturing, temporary plugging, and diversion fracturing and foam fracturing are put forward. The research method in this paper is targeted at different geological conditions so it can be used to guide the treatment of low-yield and low-efficiency wells in other CBM blocks, and it has very important significance for revitalizing the existing low-efficiency CBM assets and improving the development efficiency of CBM.

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1. Introduction

At present, the research of CBM development mainly focuses on three aspects: the main controlling factors of CBM productivity, geological characteristics, and the selection of sweet spot development. The main controlling factors of productivity mainly involve the resource endowment of coalbed methane, the transformability of the coal reservoir, and the formulation of the production system in the later stage of coalbed methane wells. Because the three aspects involve three different specialties, less work is currently being conducted on joint studies of the three. From the perspective of geology, engineering, and drainage, Feng Qing studied various factors affecting the gas and water production of a coal seam in a block of Qinshui Basin, established a typical production curve model, proposed a method to judge the damage types of low-production wells, established the screening criteria of low-production wells with a high production potential, and carried out secondary reconstruction. The research results show that the effects of geological, engineering, and drainage factors on reservoir productivity cannot be ignored. Among them, factors such as the local subsidence column, fracturing fluid immersion time, abnormal fracturing construction, drainage and production interval, production aging, and fluid drawdown rate have greater damage on the reservoir [1]. In order to analyze the impact of reservoir damage on coalbed methane well productivity during coalbed methane drainage and production, Cheng Qiao took the Chengzhuang block in the southern Qinshui Basin as an example to analyze the drainage and production characteristics of 22 coalbed methane wells, divided them into high-, medium- and low-production wells, defined the time of drainage damage of different production wells, and established a model for the identification of drainage damage of coalbed methane wells [2].

In recent years, with the diversification of analysis methods and the more refined description of geological characteristics of coal reservoirs, the analysis of the causes of low production has become more and more in-depth and accurate. By analyzing the causes of low production of vertical wells in the Zhengzhuang block in the southern Qinshui Basin, Jia Huimin proposed targeted stimulation measures, analyzed the stimulation mechanism and geological adaptability of relevant measures, optimized the construction parameters of stimulation measures, and carried out practical verification. Research and practice results show that in areas with large burial depths, it is difficult to open fractures, and the implementation of repeated fracturing can make the fracture turn and increase the fracture length, resulting in better production yield [3]. In order to identify the causes of low-efficiency wells and improve the productivity of coalbed methane wells, Li Ying analyzed the coupling relationship between high-yield wells and geological factors from the perspective of the integration of geology and engineering, combined with geological conditions and engineering factors; revealed the causes of low-efficiency wells under the influence of geology, drainage, and engineering; and put forward corresponding transformation measures. A comprehensive analysis of the treatment effect of low-efficiency wells shows that the pickling effect is better, the effect of vibration plugging is not obvious, and the construction parameters should be strictly controlled for secondary fracturing. To solve the problem of the low production and low efficiency of coalbed methane wells, we should start from well location deployment, carry out well location design and construction through the integration of geology, engineering, drainage, and production, and carry out effective and reasonable measures to increase production [4]. Zhang Yi made a detailed analysis of the influence of geological factors (structural location, collapse column, fault, etc.), engineering factors (reservoir pollution during drilling and completion and hydraulic fracturing, etc.) and drainage factors (casing pressure control, liquid discharge speed, power outage, and pumping stop, etc.) on gas production from a single coalbed methane well, and expounded nested drilling, short-radius hydraulic jet drilling, sidetracking of small holes, and secondary (repeat). Based on the characteristics and advantages of hydraulic fracturing and other stimulation technologies, the applicable characteristics of different stimulation technologies are given based on the analysis of the causes of low-production coalbed methane wells [5]. Li Yong systematically analyzed the causes of low production affected by "geological reservoir conditions, engineering construction transformation, and drainage management control", analyzed related technologies and the application effects of secondary transformation of coalbed methane wells, and provided suggestions for the targeted transformation of different types of low-efficiency wells. The research shows that the main reasons for the low production of coalbed methane wells that can be re-reformed include insufficient fracture expansion, coal powder blockage in fractures/pipe columns, and a limited pressure drop area. In the transformation, factors such as the coal structure distribution, primary fracture shape, reservoir permeability, changes in gas and water production, drainage, and control equipment applicability should be considered. Secondary transformation technology can be divided into physical methods, chemical methods, microbial methods, and other methods. Secondary hydraulic fracturing, indirect fracturing, and waterless fracturing technology as physical methods and acidification and reflection enhancement and foam pickling technology as chemical methods are widely used. In secondary reconstruction, targeted technologies should be selected according to the geological conditions, the effect of the primary reconstruction, and the situation of engineering drainage and production so as to avoid the re-damage of the reservoir, achieve effective reconstruction, and improve the gas production of a single well and pattern of coalbed methane wells [6]. Based on the actual production site, Li Yangmin summarized three types of reservoir damage caused by improper drainage and production control: pulverized coal blockage, the formation of a gas lock, and stress closure. The mechanism and production situation were studied, and it was analyzed that pulverized coal blockage was the most important reservoir damage [7]. By extracting the typical parameters of 59 coalbed methane wells in the Shizhuang block, Jiang Shanyu analyzed the dynamic characteristics of coalbed methane wells in this block; studied the effects of the fracture structure, pressure fracture type, and rock combination of the coal seam top and floor on the coalbed methane well drainage and production dynamics; and put forward reasonable development countermeasures accordingly. When selecting well locations for CBM development, it is important to select well locations in CBM-rich areas away from fault structures with vertical fractures and a good combination of top and bottom lithology. In the combined mining of multiple coal seams, attention should be paid to avoiding the drainage of potential high-water coal seams to ensure the effective production of coalbed methane [8]. Xue Haifei, aiming at the low yield and low efficiency of CBM development in the Shizhuang block, Qinshui Basin, discussed the influence of geological and engineering factors on CBM development based on the analysis of a large number of actual production data. The research shows that the ground stress and coal fabric are the key geological factors affecting the stimulation effect of coalbed methane well fracturing. In the process of forming fractures through fracturing, the extension effect of fractures and the supporting effect of fractures are mainly affected by the ground stress. Because some coal reservoirs are located in complex structural areas, the coal body structure is relatively broken, and coal powder is easy to form in the process of fracturing and blocks the seepage channel, resulting in a poor fracturing effect. In addition to the geological characteristics of the coal reservoir itself, the fracturing effect is also affected by construction parameters. Selecting a fracturing fluid with less damage to the reservoir and formulating reasonable construction parameters are also necessary conditions for obtaining a better fracturing effect [9]. Focusing on the Shizhuang North block, Lu Xiaoxia used comprehensive analysis of production data to study the gas production characteristics of deep coal seams, variation rules of drainage and production, and production dynamics of typical wells with different production rates, and put forward key influencing factors of deep coalbed methane productivity [10]. Ni Xiaoming took typical coalbed methane wells in Qinshui Basin as the research object, and analyzed the reasons for the inefficient formation of coalbed methane wells in real estate mainly from three aspects: resource endowment of coalbed methane, development technology (including drilling technology and fracturing technology), and late drainage and production systems. On this basis, targeted technical countermeasures for different reasons of low production were proposed through a laboratory acid deconsolidation test, simulation study on the optimization of fracturing parameters, principle analysis of deconsolidating the coal clogging process, and principle analysis of reducing the pump hanging depth to increase production, etc. [11]. Wang Kaifeng analyzed the causes of low production of typical wells by analyzing the coal body structure and roof and floor characteristics of the coal seam, combined with a hydraulic fracturing effect analysis, and compared them with the drainage and production system of high-production wells. The results show that the effect of hydraulic fracturing directly affects the productivity of coalbed methane wells and may also communicate with aquifers to cause low productivity of coalbed methane wells while improving the permeability of coal reservoirs. In the early stage of drainage and production, an unreasonable drainage and production system is also an important reason for the low production of high-potential wells. The reasonable control of these two stages will have an impact on the whole gas production process in the future. Controlling the fracture height and fracturing scale to avoid penetrating the waterproof layer, maximizing the far-reaching expansion of fractures in the coal seam, and rationally developing the drainage and production system are the keys to the long-term and efficient development of wells with CBM production potential after secondary fracturing reconstruction [12]. In order to explore the reasons for the low production of coalbed methane well in the soft and low-permeability coal seam in Zhaozhuang block, southern Qinshui Basin, JiYangtze River took the No. 3 coal seam as the research object and analyzed the pore and fracture development characteristics and clay mineral composition of the target coal seam by means of liquid nitrogen adsorption, scanning electron microscopy, and X-ray diffraction so as to identify the physical characteristics of the soft and low-permeability reservoir. Through a water-sensitive damage experiment, the mechanism of the low production of coalbed methane in the soft and low-permeability reservoir was further analyzed [13].

At present, there is a certain proportion of low-yield and low-efficiency wells in each CBM development block. With the further clarification of the causes of low production, development technology has also made progress. This has allowed developers to take steps to revitalize low-production wells. Hu Qiuping used a multi-level fuzzy comprehensive evaluation method to analyze the main controlling factors of the productivity of low-efficiency coalbed methane wells from three aspects, such as resource conditions, production conditions, and development conditions, and gave the applicability evaluation of drainage and production equipment. The analysis results show that the multilevel fuzzy evaluation method can be used to obtain five indexes that affect the productivity of coalbed methane wells, namely, the gas content, buried depth, permeability, pulverized coal production, and discharge rate. According to the five main indexes, the optimization work of coalbed methane drainage and production systems and processes can be carried out. In view of the two important factors pulverized coal production and discharge and recovery speed, the adaptability analysis of the commonly used “three-pump” equipment, screw pump, electric submersible pump, and jet pump, for coalbed methane drainage and recovery was carried out [14]. Yao Hongsheng studied the production characteristics of the south Yanchuan CBM block and believed that the scale of fracture network formed by reservoir reconstruction was the main reason for the high yield of CBM. Due to the lack of development experience in the early stage, the scale of the fracture network is not enough, and relatively large low-yield and low-efficiency wells are formed. The difference coefficient of horizontal stress is the key parameter for forming a complex joint network, which is inversely proportional to the degree of forming a complex joint network. The method of multiple fracturing can reduce the difference coefficient of horizontal stress and realize a large-scale complex fracture network. Through the field fracturing test, the method of changing the fracturing flow rate successively was carried out, and single fracturing was upgraded to multiple fracturing. Monitoring showed that the fractures formed by fracturing also changed from a single fracture to a complex fracture network. Through the later production effect analysis, with the help of a complex fracture network, gas production and the development efficiency of coalbed methane wells are improved [15]. Wang Chengwang studied the reasons for the low production of some coalbed methane wells in Hancheng block using the data of geology, fracturing, and discharge and production dynamics. It is considered that the main factors that cause the low production of coalbed methane wells are poor reservoir physical properties, faults affecting the gas content and gas saturation, fracturing communication of adjacent water layer in multi-layer mining, an imperfectly developed well pattern, failure of effective reservoir pressure reduction due to overflow recharge, and local structural coal development, making it difficult to fracture the seam and drain coal powder blocking the seepage channel. Through technical research, targeted technologies such as cross-layer fracturing, water plugging, acid plugging, workover process optimization, and increased discharge and production intensity of old wells have been formed [16]. Shao Xianjie analyzed the influencing factors of middle- and low-production wells from two aspects of geology and engineering. There are six main influencing factors: (1) a thin production layer thickness and limited controlled reserves of a single well; (2) poor reservoir physical properties and low production; (3) the fault communicates with the fracture, and adjacent layer water channeling occurs; (4) no cementing or poor cementing quality in shallow layers, surface water channeling along the outside of the pipe, and large displacement; (5) fracturing measures do not reach the design scale, the effective seepage radius is small, and stable production time is short; and (6) the drainage and mining system is unreasonable, resulting in stress sensitivity and a rapid production decline. According to the research results, the corresponding adjustment schemes and measures are put forward as follows: optimizing the perforating interval and increasing the thickness of the production layer; repeated fracturing is implemented in the appropriate production stage to expand the drainage area; pipe channeling well plugging workover; lateral drilling of a horizontal well after sealing the fault cross-flow well; establishing a reasonable drainage and production system; and extending the stable production period through permeability engineering interventions [17]. Cao Yunxing studied and developed reservoir protection stimulation technology for low-production wells with low water pressure and low pressure, and conducted engineering tests in Yuwu well field, Lu 'an Mining area, achieving the expected stimulation effect [18]. In order to explore more efficient coal seam transformation technology, Wang Liguo introduced in-layer temporary plugging to fracturing technology in combination with conventional oil and gas field temporary plugging and steering theory, and analyzed the steering mechanism, steering radius, influencing factors, and adaptability of fractures in coal layers. In order to ensure that the in-layer temporary plugging can transform the coal seam to a greater extent, a temporary plugging agent is selected, and the particle size, dosage, adding technology, and construction displacement of the temporary plugging agent are optimized. Field tests of in-formation temporary plugging and turning fracturing of three wells have been carried out in the field, and good application results have been achieved [19]. In order to improve the gas production effect of coalbed methane wells, Li Quanzhong studied the factors affecting the gas production of coalbed methane wells from the geological static parameters and engineering dynamic parameters of coalbed methane development. Based on the reservoir parameters, geological characteristics and development data of 12 typical CBM wells in a block of Qinshui Basin, Shanxi Province, he analyzed 24 factors in seven aspects, including CBM resource characteristics, coal reservoir seepage, structure, energy characteristics, drilling, fracturing, and drainage and production engineering, from the perspective of geology and engineering factors. He studied the degree of control of various factors on gas production of coalbed methane wells [20]. Kang Yongshang analyzed the change in stress near the wellbore in the process of drainage and gas production of coalbed methane wells in China and believes that the rapid drop of the wellbore liquid level leads to a decrease in the permeability near the wellbore coalbed methane wells that cannot obtain long-term and sustained high output, resulting in a low development efficiency. In view of the characteristics of low permeability and compressibility of coalbed seams, the mathematical model of coalbed methane drainage and production is established using the theory of underground seepage mechanics, and the quantitative solution of the coalbed methane drainage and production system at the same time is given as the working system of coalbed methane drainage and production that is optimized by means of numerical simulation. A step-by-step pressure relief system can expand the volume of the pressure drop funnel, increase the resolution range of CBM, and increase the cumulative gas production of CBM wells [21]. Nitrogen foam fracturing has been a popular fracturing method for coal reservoirs in recent years. Nitrogen foam fracturing can be used to fracture water-sensitive reservoirs. As with hydraulic fracturing, it is also necessary to study the construction parameters of nitrogen foam pressure to achieve the optimal fracturing effect. By comparing a large number of nitrogen foam fracturing construction parameters and corresponding fracturing effects, Li Hengle classified the nitrogen foam fracturing construction curves, clarified the corresponding productivity characteristics of different types of fracturing construction curves, and optimized the nitrogen foam fracturing construction parameters on this basis [22]. Zhang Jianguo studied the technology of secondary fracturing to increase production in accordance with the characteristics of the block coal reservoir in this area. Through the identification of coal reservoir characteristics, the research on the mechanism of secondary fracturing to increase production and the change in fracturing construction ideas, four kinds of stimulation technologies adapted to different coal reservoir characteristics have been established, and 80 wells have been applied in the field [23]. Zhang Cong formulated a reconstruction plan for low-production wells in the area and summarized and analyzed the application effect of plugging secondary fracturing in CBM development in detail. The research shows that the series hydraulic fracturing technology is a more effective means to increase production in this area. Electric pulse plugging removal and radial hydraulic injection are new attempts and favorable supplementary technologies, but their effects on stimulation remain to be further observed [24]. Yan Xinlu studied the feasibility of the secondary reconstruction of low-efficiency wells by establishing prediction models of reservoir pressure, reservoir dynamic permeability, fracture dynamic permeability, and fracture length, and predicted the effect of reconstruction using a numerical simulation method. The results show that the permeability of low-efficiency wells decreases first, then increases, and then recovers to the initial level. The initial fracturing effect is good, but due to the effective stress effect in the later stage, the fracture partially fails, the fracture permeability decreases, and gas production decreases. After secondary fracturing, the daily gas production of low-efficiency wells gradually increases. However, due to the uniform distribution of reservoir water caused by long-term low production, high production is not achieved in the short term. Therefore, it takes some time to re-drain and depressurize the wells to improve stable gas production [25]. Zhao Wupeng deeply analyzed the causes of low production of production wells in Zhengzhuang block from the two aspects of geology and fracturing construction, and proposed that based on the geological characteristics of Zhengzhuang block, an active water fracturing fluid should be selected as the fracturing fluid in the process of reservoir reconstruction, fracturing displacement should be optimized according to geological characteristics in the fracturing process, and the same well should adopt different construction displacements at different times in the fracturing process. Especially for the low-production wells with a large buried depth and very low permeability, the fracturing technology of “large fluid volume, large sand volume, and variable displacement” is proposed to ensure that the reservoir reconstruction can achieve the expected effect. Due to the decrease in production of production wells caused by coal seam plugging, it was suggested to adopt the secondary hydraulic fracturing reform measure of plugging relief, and the experimental measure of microbial plugging relief was first implemented in Zhengzhuang block, and the effectiveness of this technology in the treatment of low-production wells in Zhengzhuang block was explored [26].

There are widely distributed cutting systems in coal reservoirs, which is an important factor that distinguishes coal reservoirs from other reservoirs. Therefore, for the numerical simulation research of coalbed methane, the cutting system of the coal reservoir must be considered. According to the characteristics of coal reservoirs, Xu Jiaxiang established face and end cutting systems with different densities by means of random simulation, taking into account the stress sensitivity effect and matrix shrinkage effect of coal reservoirs. On this basis, he carried out numerical simulation research on coalbed methane, further improving the numerical simulation accuracy of coal reservoirs [27]. Hydraulic fracturing is a necessary means of coalbed methane development, and the numerical simulation of coalbed methane cannot be carried out without a fracture numerical simulation model. Gong Zewen carried out numerical simulation research under different conditions of fracture expansion based on geological models with different levels of principal stress differences, and identified the influences of different levels of principal stress on fracture extension and coalbed methane well productivity. The productivity of coalbed methane wells under different fracture propagation conditions was predicted [28].

2. Materials: Geological Characteristics of Block A

Block A is located in Qinshui Basin and belongs to Jincheng City, Shanxi Province. The characteristics of the No. 3 coal reservoir in the study area are evaluated using the logging data and production data of the parameter well and development well. The thickness distribution of the No. 3 coal seam in the east of block A is relatively stable, and the variation is not large in general. The thickness of coal seam is mainly between 4.0 m and 8.0 m, with an average of 6.0 m. Collapse columns develop near the southern part of the block, resulting in the loss of the coal seam. Drilling reveals that the minimum thickness of the No. 3 coal seam is 1.8 m and the maximum thickness is 14.3 m. The burial depth of coal seam No. 3 in the southeast of block A is small, and there is an obvious trend of increasing from south to north in general. Drilling revealed a shallow depth of 451 m (Figure 1).

Due to less data for parameter test points, east block A of the No. 3 coal seam has a measured gas content between 2.34 and 19.16 m^3/ton, and the change is bigger. According to the isothermal adsorption principle, the critical desorption pressure is the pressure when the coal seam gas first appears, and so for the CBM well that has been put into operation, the flow pressure at the bottom of the well can be used to calculate the gas content. At the same time, in order to improve the calculation accuracy, the measured critical desorption pressure of parameter well is used to correct the bottom-hole flow pressure when gas is seen. Based on the above work, the gas content of the No. 3 coal seam in area A is fitted. The overall gas content ranges from 3.55 m^3/ton to 24.20 m^3/ton, with an average of 14.12 m^3/ton, among which the gas content is higher in the middle and lower in the south and east.

According to the two-dimensional seismic data with a network density of 2 km × 4 km, 153 faults are interpreted in total, including 96 normal faults and 57 reverse faults, mainly normal faults, and the scale of reverse faults is obviously smaller than normal faults. The fault strike is mainly NNE and NNW, and the tendency is mainly a west dip or east dip. Block A has been deployed with 3D seismic exploration work, covering an area of 17.85 km^2, and the total area of the collapse column of the No. 3 coal seam in this area is 0.471 km^2.

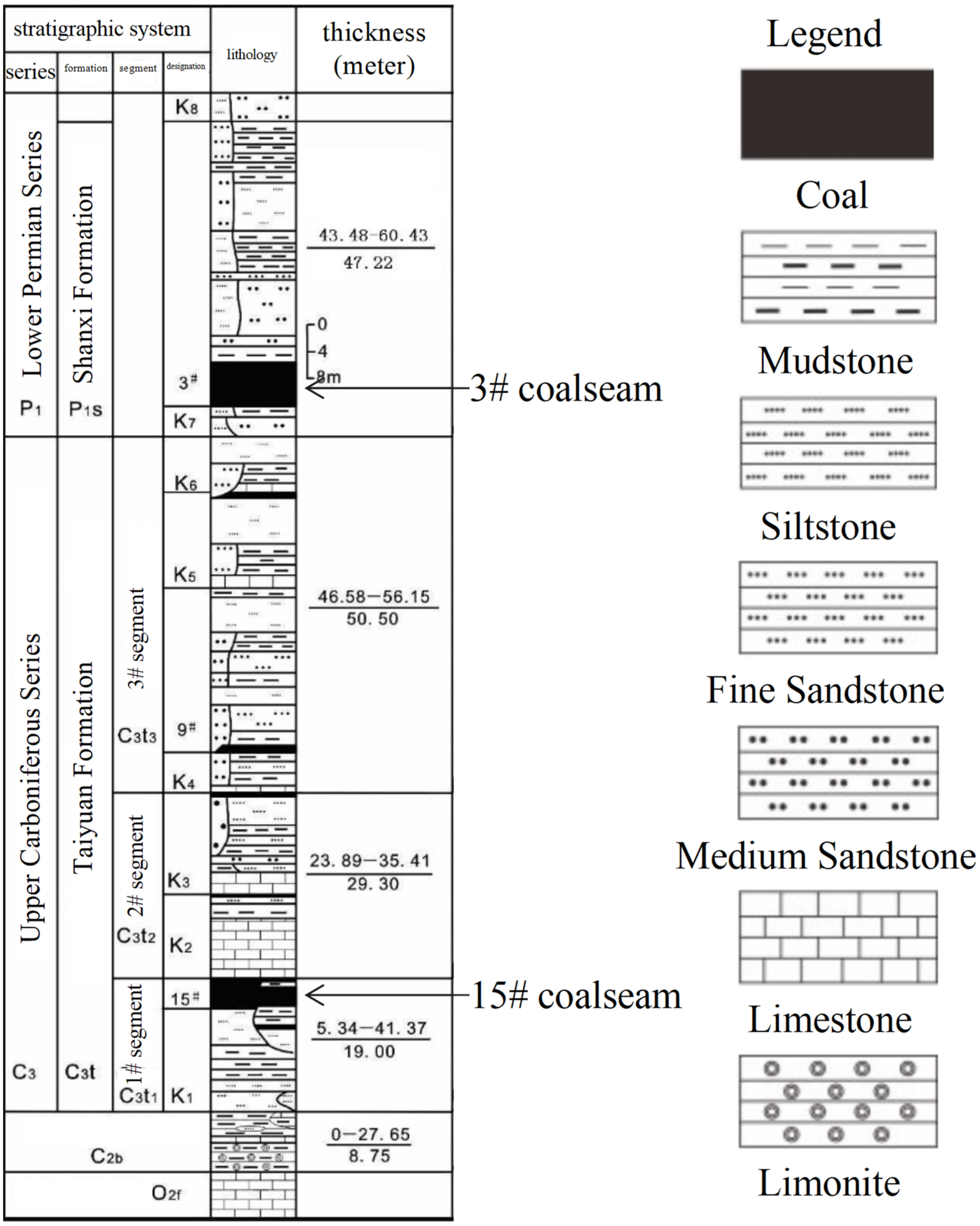

Figure 1. Block A lithological profile.

3. Methods

3.1. Criteria for Identifying Low-Production and Low-Efficiency Wells

Due to the great differences in geological conditions and reservoir properties of different blocks, the typical curve method is mainly used in the process of studying the identification criteria for low-production and low-efficiency wells. The typical curve method is to use the typical parameters of the block (including the gas content, thickness, permeability, etc.) to conduct numerical simulation research and obtain the typical curve of the block. In order to apply the average gas production of coalbed methane to characterize the gas production capacity of coalbed methane, it is necessary to average the typical curve, that is, to obtain the average gas production of each time node, obtain the average typical curve, and then obtain the template of low-production and low-efficiency wells. At present, the coal bed methane wells whose average gas production is below the lower limit of the average typical curve are classified as low-production and low-efficiency wells (Figure 2).

The formula for averaging the typical curve is as follows:

$$q_i = \frac{Q_i}{T_i}$$

in the formula,

q_i is the average gas production at time i, cubic meter per day;
Q_i is the cumulative gas production at time i, cubic meter;
T_i is the cumulative days of production at time i, days.

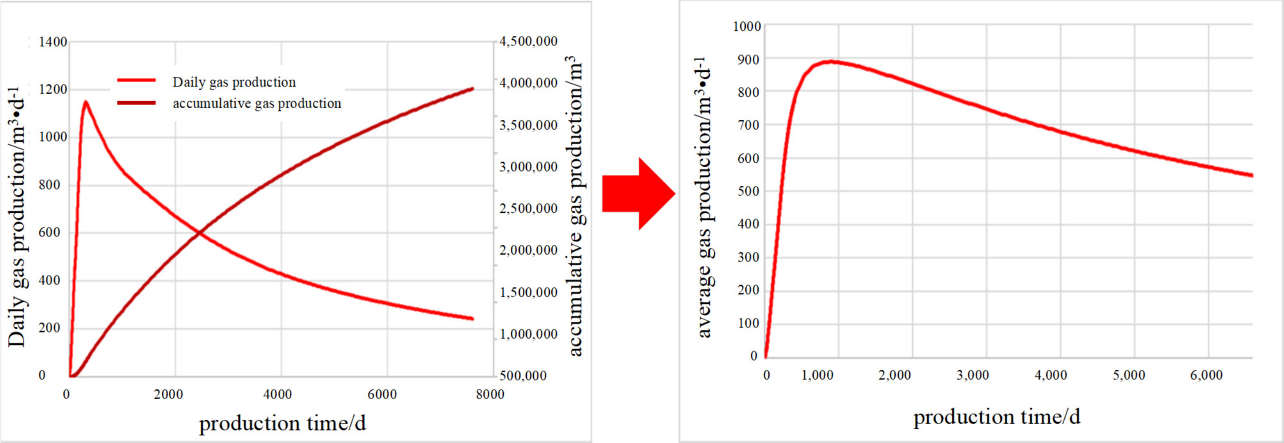

Figure 2. Translation from daily gas production to the average typical curve.

Considering the current production cost of a single coalbed methane well (mainly including the management fee, discharge and production service fee, etc.) and gas price, the economic limit production of a single well can be calculated, and the low-production and low-efficiency wells are further divided into low-production and low-performing wells I and II (Figure 3).

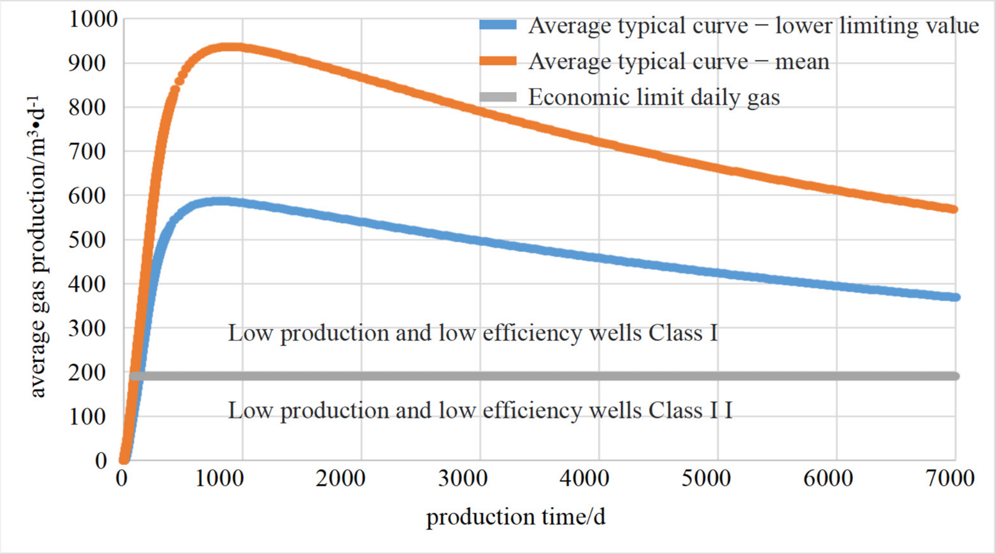

Figure 3. Identification chart of low-production and low-efficiency wells.

There are many factors affecting the productivity of coalbed methane wells, but there are three important types. Firstly, geological factors determine the preconditions for CBM resource endowment in coal reservoirs and mainly include resource abundance, which represents the enrichment degree of CBM; reservoir permeability, which determines the difficulty of CBM seepage; and coal body structure, which determines the effect of coal reservoir transformation. Second are engineering factors, since coalbed methane can be effectively exploited only after reservoir transformation, and so the quality of transformation also determines the productivity of coalbed methane wells. Engineering factors are divided into the transformation intensity and transformation adaptability of coal reservoirs, and transformation adaptability is attributed to geological factors. The third factor is the drainage and production system in the later stage. The seepage velocity in a coal reservoir will affect the flow and precipitation of pulverized coal, and the precipitation of pulverized coal will affect the permeability of the coal reservoir and then affect the gas production of coalbed methane wells. Under normal circumstances, the resource abundance and coal structure can be well predicted by technology, but the coal reservoir permeability is difficult to predict, which can be attributed to unexpected factors. The effective evaluation method of the fracturing effect is underground microseismic monitoring, but it is expensive. At present, the application of coalbed methane production wells is few, and other methods to evaluate the fracturing effect are difficult, which can be attributed to unexpected factors. The drainage and mining system in the later period is determined by man and is the expected factor. At the same time, with the progress of CBM development technology, the environmentally friendly development mode has been constantly improving, and so there is basically no environmental problem under the current development technology.

3.2. Low-Production and Low-Efficiency Well Treatment Process and Division

In the process of treating low-production and low-efficiency wells, there are four main steps: (1) Judging whether a well is a low-production and low-efficiency well according to the discriminant plate of low-production and low-efficiency wells, and judging whether a low-production and low-efficiency well is a Class I well or a Class II well according to the economic limit of gas production. (2) The causes of low production are analyzed for low-production wells. The causes of low production mainly include geological causes, engineering effects, and the effects of the production and discharge system. (3) According to different causes of low yield, measures are analyzed, and different methods are adopted to increase yield (Figure 4).

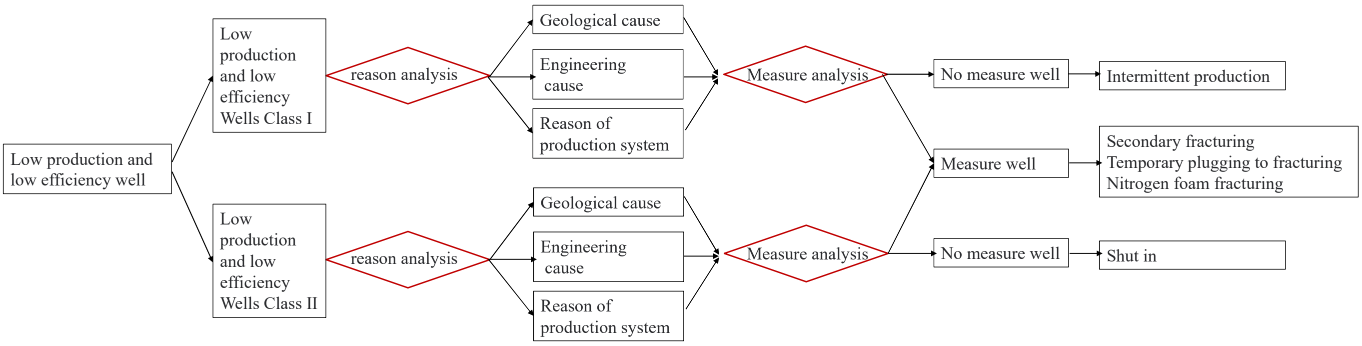

Figure 4. Flowchart of the treatment of low-production and low-efficiency wells.

By combining the actual gas production of each single well in the block, the current actual gas production is converted into the average gas production, and it can be judged whether the well is a low-production and low-efficiency well by throwing it into the low production and low efficiency well chart. At present, the operating cost of a single well in block A is 75,500 yuan/well/year, the gas price is 1.87 yuan/m^2, and its economic limit of production is 122 m^2/day. According to this parameter, low-yield and inefficient wells can be classified as Class I or Class II (Figure 5).

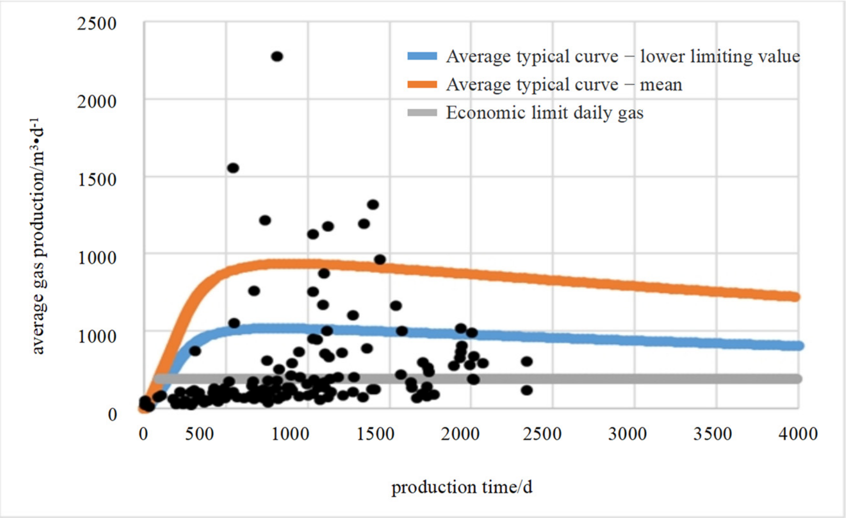

Figure 5. Judgment of low-production and low-efficiency wells in block A.

4. Discussion

The low production and low efficiency of coalbed methane wells are caused by many factors, but there is a main control factor at the same time, and only by focusing on the main control factor can we propose more effective measures to increase production. When analyzing the causes of low production in area A, we first start from the geological conditions of the coal seam and analyze the causes of low production dominated by geological conditions, such as the gas content and faults. Then, the engineering influencing factors of other wells are analyzed, the engineering reconstruction effect of each well is analyzed, and the causes of low production dominated by engineering factors are clarified. Finally, the drainage and production system of the remaining wells is analyzed, and the low-production wells caused by an unreasonable drainage and production system are screened.

4.1. Geological Cause

4.1.1. Low Resource Abundance

The overall thickness difference of block A is small, with an average of 6.3 m, but the gas content distribution shows strong heterogeneity. According to the CBM abundance calculation method, the gas content determines the abundance distribution. The southern and eastern parts of the block have relatively low gas contents. Based on the average daily gas production and gas content of all production wells, when the gas content is less than 9.5 cubic meters per ton, the development effect of coalbed methane wells is poor and all of them are low-production and inefficient wells (Figure 6). For all the wells in Figure 6, we can obtain the relationship between the average CBM gas production and coal reservoir gas content, and gas content of gas wells with average gas production greater than 600 m^3/day is greater than 9.5 m^3/ton. However, low-production wells are also required in areas with a high gas content, which indicates that a high gas content is a necessary condition for the formation of high-production coalbed methane wells, but it is not a sufficient condition, because to obtain high-production wells, good seepage conditions, an effective reservoir reconstruction effect, and a stable production system are also required.

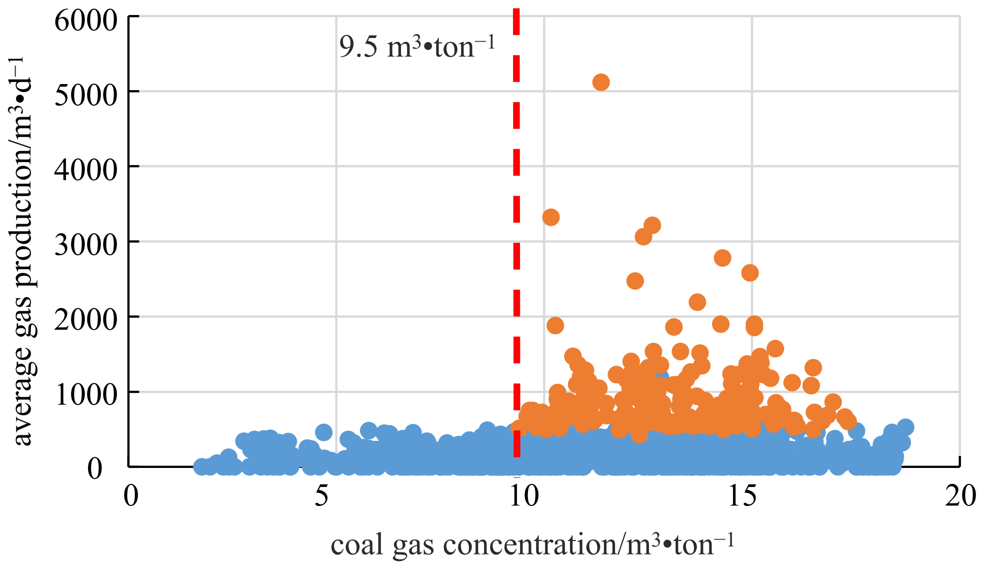

Figure 6. Relationship between the gas content and average daily gas production per year.

Based on the above understanding, wells with a gas content less than 9.5 m^3/t in the southern and eastern regions of block A are classified as low-productivity and low-efficiency wells caused by low resource abundance. Due to the low resource abundance of these wells, the current stimulation measures cannot achieve an effective stimulation. There are two suggestions for this part of wells: (1) the wells whose current gas production is less than the economic limit should be shut down, and (2) wells with a current gas production greater than the economic limit are recommended to continue to be discharged.

4.1.2. Fault-Related Topography

Block A is a southwest inclined monoclinal structure with an average dip of about 5°, and the main coal seam structure has strong inheritance. The scale of faults is small, the reverse faults are dominant, and the strike is mainly NNW and NE. The vertical break distance is 15~46 m and the plane extension length is 66~693 m.

Based on the two-dimensional seismic interpretation results, the fault development in the northern part of the block shows that compared with the southern CBM wells, the northern CBM wells produce more water and lower gas. In Figure 7, the horizontal coordinate is the distance between the coalbed methane well and the fault, and the vertical coordinate is the average daily water volume of the coalbed methane well. It can be seen from the regression scatterplot of the coalbed methane well distance from the fault and daily gas production, the closer to the fault, the more water the well produces. This is mainly because in the fracturing process of coalbed methane wells, the closer the distance between coalbed methane wells and faults, the higher the risk of communication faults in the fracturing process. If a fault is connected in the fracturing process, a large amount of water will enter the gas well through the fault due to the high conductivity characteristics of the fault, resulting in increased water production of the coalbed methane well (Figure 7). The wells with large water production in the north can be divided into two types, namely, the type of water production with no drop and the type of water production with decline. The type of water production with no drop refers to the coalbed methane wells that maintain a high level of water production after they are put into operation, and the water production index is relatively stable with the increase in discharge and production time. The water production decline type means that after the CBM well is put into operation, the water production remains at a high level in the early stage, but with the increase in discharge and production time, the water production index gradually decreases, water production decreases, and gas production increases. As for CBM wells with non-falling water production, due to the fault communication aquifer, water production that has been maintained at a high level, and almost no gas production, it is recommended to shut down these CBM wells. As for the coalbed methane wells with decreasing water production, the impact of faults is relatively small. With the progress of drainage and production, water production can gradually decrease and the gas production increases after the coal seam begins to depressurize; so, it is recommended to continue the drainage and production of this part of coalbed methane wells.

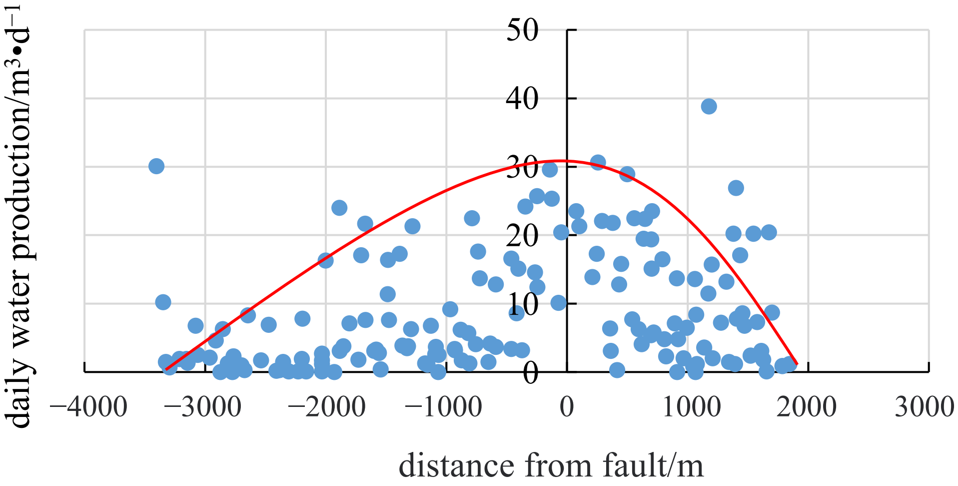

Figure 7. Relationship between the distance from the fault and daily water production.

4.1.3. Subsidence Column Effect

As it is known, the distribution of subsidence can be explained by the three-dimensional seismic interpretation of the blocks. At present, through 3D seismic interpretation, it is analyzed that there are eight subsidence columns in this area. After analyzing the coalbed methane wells around the eight subsidence columns, the subsidence columns have a significant impact on the production of coalbed methane wells. The collapse column represents the loss of a coal seam, and so the closer a coalbed methane well is to the collapse column, the more serious the loss of the target coal seam around it. Accordingly, the target coal seam does represent a decrease in the controlled reserves of the well. Therefore, the closer to the collapse column, the lower the gas production of CBM wells. Figure 7 represents the influence of a collapse column on gas production of coalbed methane wells. In Figure 7, the horizontal coordinate is the distance between the coalbed methane well and the collapse column, and the vertical coordinate is the average gas production of the coalbed methane well. The closer the subsidence columns are, the more obvious the impact will be (Figure 8). The relationship between the distance to the collapse column and the output of coalbed methane well is quantitatively analyzed. The analysis results show that when the coalbed methane well is within 200 m of the subsidence column, the drainage and production effect is greatly affected, and the coalbed methane wells in this area are all low-yield and inefficient wells. Therefore, coalbed methane wells within 200 m of the subsidence column are classified as low-productivity and low-efficiency wells affected by the subsidence column. For the low-production and low-efficiency wells affected by the collapse column, due to the low production caused by geological factors, the current stimulation measures cannot achieve an effective stimulation. It is recommended that the wells with a current daily gas production less than the economic limit of production be shut down, and the wells with a current daily gas production greater than the economic limit of production be continued to discharge production.

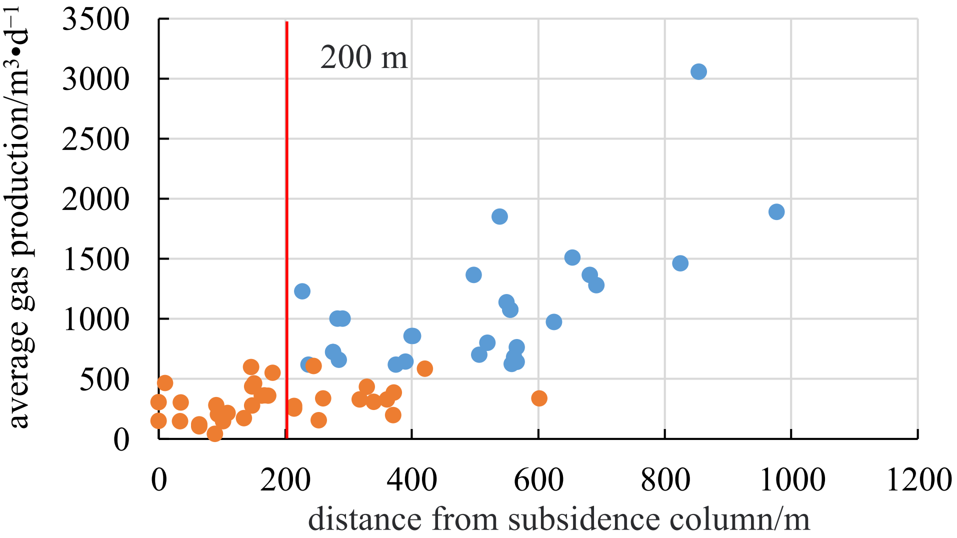

Figure 8. Relationship between the distance from the collapse column and average daily gas volume.

4.2. Fracturing Effect

4.2.1. Fracturing Curve Evaluation

Coal reservoir fracturing is an important step to realize the efficient development of coalbed methane in high-rank and low-permeability coal reservoirs, and is a key factor affecting the production of coalbed methane wells. After discriminating the geological causes, the fracturing effect of the remaining wells is evaluated. According to the evaluation of the fracturing construction curve of coalbed methane wells, the fracturing construction curve can be divided into four types, namely, a stable type, declining type, rising type, and fluctuating type. Among them, the stable type and descending type have relatively good effects of fracturing reconstruction, while the rising type and fluctuating type have poor effects (Table 1).

(1) Stable type: The stable refers to when the displacement is stable or rising, the sand ratio is stable or slightly increased, the pressure remains relatively stable, the sum of fracturing fluid and filtration loss and the injected fluid reach dynamic equilibrium, and the pressure in the fracture is stable. The fracturing effect shown by this fracturing construction curve is relatively good, and the actual production effect is also ideal.

(2) Decline type: The decline type means that when the displacement is stable, the sand ratio is stable or increased, and the pressure remains relatively stable after dropping to a certain value. The fracturing curve shows that the fracture in the coal seam extends normally and the net pressure in the fracture is stable, which is an ideal construction curve.

(3) Rising type: The rising type is when the displacement is stable, the sand mixing ratio is stable or increased, and the pressure continues to rise. The reason for this construction curve is that with the increase in the sand ratio, proppant is continuously filled inside the fracture, and with the loss of fracturing fluid, part of the proppant settlement forms a sand bank at the bottom of the fracture and the gradual increase in the height of the sand bank makes it difficult to transport the proppant.

(4) Volatility type: The volatility type refers to a discharge stability that is higher than that of the stability of sand, and the pump pressure fluctuates within a certain scope. The reason for this construction curve is that coalbed methane is highly heterogeneous, and it is easy to produce coal powder or fine coal and rock particles under the scouring of fracturing fluid, which blocks the front end of the fracture under the pushing of fracturing fluid, affecting the expansion of the fracture end, forcing the fracture to change course and break again, and resulting in complex and irregular cracks. The

fracture propagation length of this model is limited and the development effect is not ideal.

Table 1. Fracturing parameters and production parameters of different types of fracturing curves in block A.

Fracturing Curve Type	Fracturing Fluid Usage, m^3	Fracturing Sand Usage, m^3	Fracture Half Length, m	Fracture Width, m	Peak Gas Production, $m^3 \cdot d^{-1}$	Average Gas Production, $m^3 \cdot d^{-1}$
Stable	446	46.8	73.5	1.06	2356	1285
Decline	430	45.1	65.3	1.23	1770	1118
Rising	506	50.2	20.6	1.52	800	423
Volatility	507	50.4	18.6	1.42	1632	330

By analyzing the fracturing construction curve of low-productivity and low-efficiency wells, the rising type and fluctuating coalbed methane wells are divided into low-productivity and low-efficiency wells caused by engineering factors. Due to the failure of engineering fracturing transformation in this part of the wells, the artificial fracture length extension of coalbed methane wells is limited, the coal seam transformation range is limited, and the desorption range is small, which leads to small mobilized reserves, low cumulative gas production, and a poor development effect. In order to solve the low-production and low-efficiency wells caused by engineering factors, we should take measures to expand the scope of reconstruction to increase production.

4.2.2. Analysis of the Secondary Fracturing Effect

Due to the failure of engineering fracturing reconstruction, the artificial fracture extension of coalbed methane wells is limited, the coal seam reconstruction scope is limited, the desorption range is small, the activated reserves are small, the cumulative gas production is low, and the development effect is poor. At present, 10 low-yield and low-efficiency wells for engineering reasons have been subjected to secondary fracturing. The production stimulation effect of low-yield and low-efficiency wells affected by engineering transformation is not obvious after secondary fracturing, and only five of the ten wells have achieved production stimulation, the stimulation effect is not obvious, the production increase is only about 100 m^3/d, and the secondary fracturing effect is poor (Figure 9 and Table 2).

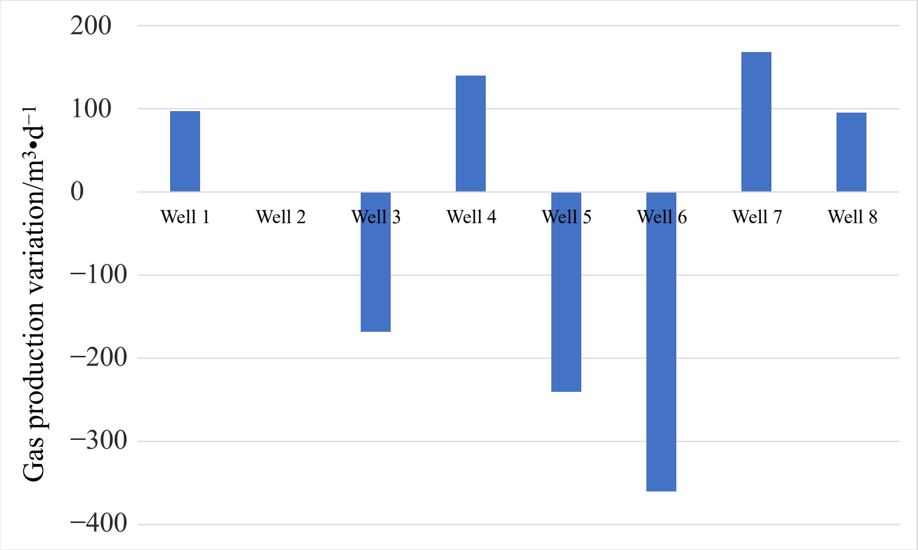

Figure 9. The project of block A affects the stimulation effect of secondary fracturing of low-production and low-efficiency wells.

Table 2. Stimulation effect of secondary fracturing of low-production and low-efficiency wells in block A.

Well Name	Production before Fracturing	Production after Fracturing	Permeability before Fracturing	Fracture Half Length before Fracturing	Discharge Range before Fracturing	Permeability after Fracturing	Fracture Half Length after Fracturing	Discharge Range after Fracturing
	$m^3 \cdot d^{-1}$	$m^3 \cdot d^{-1}$	mD	m	m	mD	m	m
Well 1	434	531	1.2	32	50	1.4	40	60
Well 2	576	382	1	44	70	0.8	44	70
Well 3	264	96	0.4	25	40	0.2	25	40
Well 4	220	360	0.4	25	40	0.7	25	40
Well 5	456	216	1.1	30	45	0.8	30	45
Well 6	600	240	1.4	30	45	0.5	30	45
Well 7	120	288	0.2	15	25	0.5	25	40
Well 8	0	95	0.3	15	25	0.2	15	25

In order to analyze the effect of secondary fracturing, a geological model was established based on the geological characteristics of block A and combined with fracturing construction parameters to simulate the fracture extension effect. The main geological model parameters and fracturing construction parameters of block A are shown in Table 3. The software used for the simulation was Meyer 3D Fracturing software, version Meyer2021.

Table 3. Fracturing numerical simulation parameter table for block A.

Well Name	Young Modulus	Poisson's Ratio	Crustal Stress	Lead Fluid Volume	Sand Mixing Fluid	Displacement Volume	Total Fluid Volume	Total Sand Volume
	GPa	/	MPa	m^3	m^3	m^3	m^3	m^3
Well 1	3.48	0.35	9.82	151	361	9.2	510	50
Well 2	3.61	0.37	8.12	183	449	9.4	642	42

According to the evaluation of the effect of secondary fracturing on these 10 wells, the production range of coalbed methane wells has not been significantly improved before and after secondary fracturing, and the fracture length after fracturing generally increases within 5 m, which does not solve the problem of the small production range caused by engineering reasons. According to the analysis, no new fractures are formed in the secondary fracturing of the previous 10 wells, mainly because the scale of the current secondary fracturing is the same as that of the first fracturing, and the fracturing fluid is still extended in the original fracture. Moreover, it can be seen from the fracturing construction curve of secondary fracturing that there is no fracture pressure in the current 10 secondary fracturing wells (Figures 10 and 11).

To further solve the problem of secondary fracturing, it is suggested to increase the scale of secondary fracturing and adopt large-scale secondary fracturing to form new fractures. Based on the research results, it is recommended that the secondary fracturing scale be four times that of the primary fracturing scale.

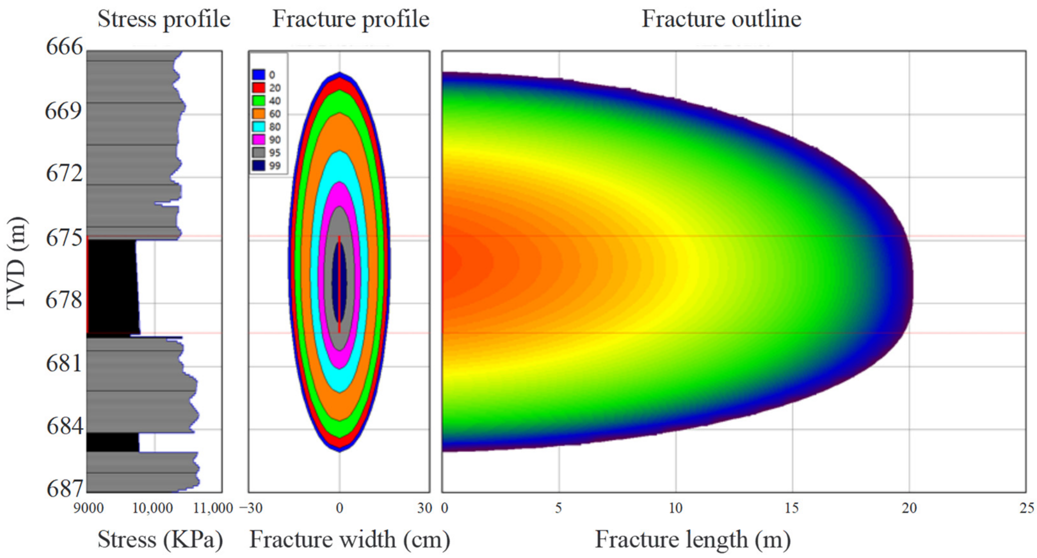

Figure 10. Well 1 fracturing simulation profile.

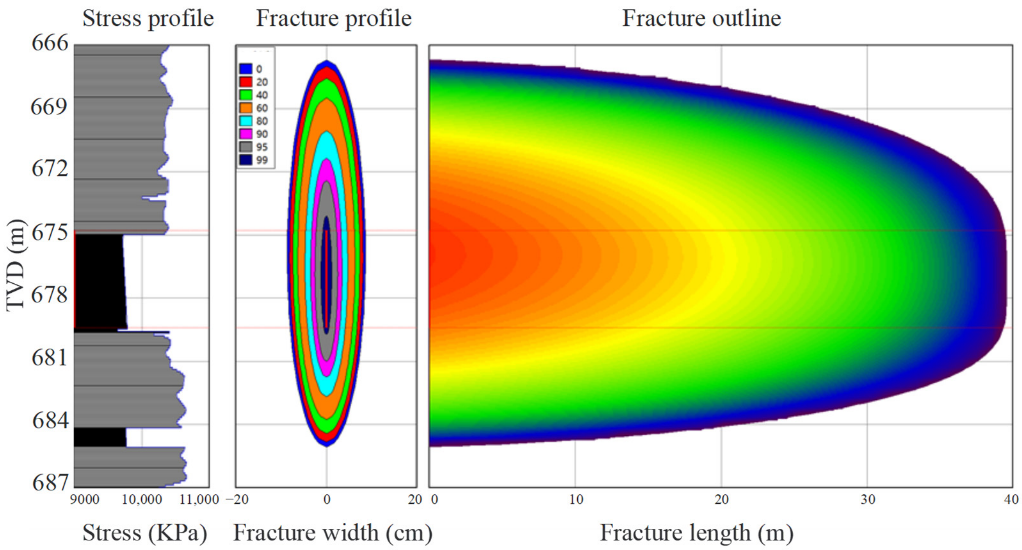

Figure 11. Well 2 fracturing simulation profile.

4.2.3. Temporary Plugging to Fracturing

During conventional secondary fracturing, fracturing fluid tends to migrate along the existing fracture with lower seepage resistance, resulting in the inability to open new fractures. Therefore, to solve this problem, it is suggested to carry out a temporary plugging and fracturing test. Temporary plugging to fracturing is to add a temporary plugging agent into the fracturing fluid, and the temporary plugging agent enters the high-permeability zone or a primary artificial fracture with the fracturing fluid to form a bridge plugging so as to realize the purpose of fracturing fluid re-fracturing the reservoir. At the same time, the temporary plugging agent can be completely dissolved in the fracturing fluid and groundwater and can be discharged to the ground with the fracturing fluid after fracturing; so, the damage to the coal seam is less.

4.2.4. Nitrogen Foam Fracturing

Due to the selective seepage of foam fluid in the formation, it has a proper sealing effect on the high-permeability area and an effect of increasing the swept area in the low-permeability area. Due to the shear dilution characteristics of nitrogen foam, the shear rate of the foam in the high-permeability area is small, the surface viscosity of the foam is high and the seepage resistance factor is large, forcing part of the nitrogen foam to flow to the low-permeability area of the coal seam. Thus, the permeability of low permeability zone can be improved, and the fracturing and influence range can be expanded. Therefore, nitrogen foam fracturing can be used to open new fractures during secondary fracturing.

4.3. Impact of the Drainage and Production System

According to the daily water production of all the drainage wells in area A, the production velocity of the block before gas appearance is within a reasonable range, and the drainage and production system affecting the development effect of coalbed methane wells is mainly the selection of the turning point pressure. Coalbed methane wells after turning point refer to the gas phase pressure, where the bottom hole flowing pressure decline rate compared with drainage decompression stage is significantly lower, namely, the bottom hole flowing pressure decline rate slows further. There is a turning point or interval between the stage of drainage pressure reduction and the stage of gas discovery (Figure 12).

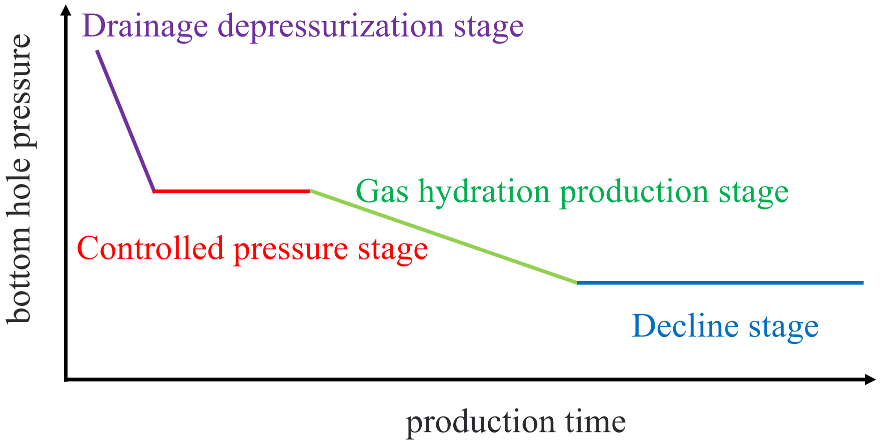

Figure 12. Variation of the bottom hole flow pressure during the gas well production cycle.

When the turning point is too high and i formation pressure step-down is inadequate, less gas is removed by desorption. When the turning point is too low, the stress sensitivity is strong and the permeability is reduced, which have great influences on late production. When the turning point is about 80% of the critical desorption pressure, the development effect is better. When the turning point is less than 40% of the critical desorption pressure, the development effect is not ideal (Figures 13 and 14). The critical desorption pressure of this model is 2.2 MPa.

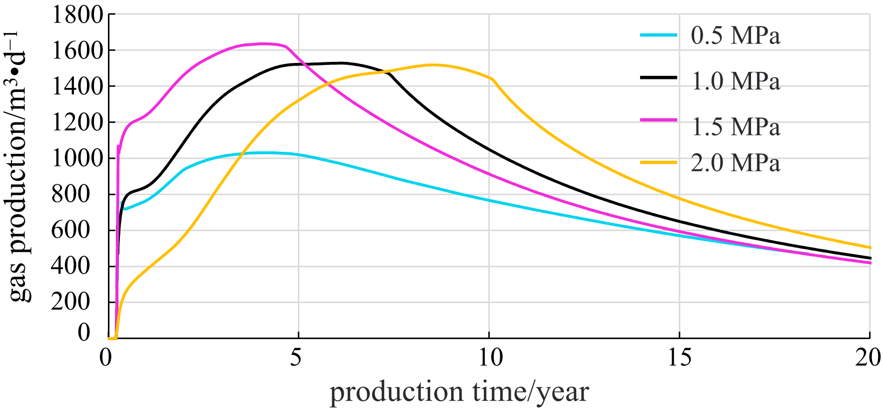

Figure 13. Gas production curves at different turning pressures.

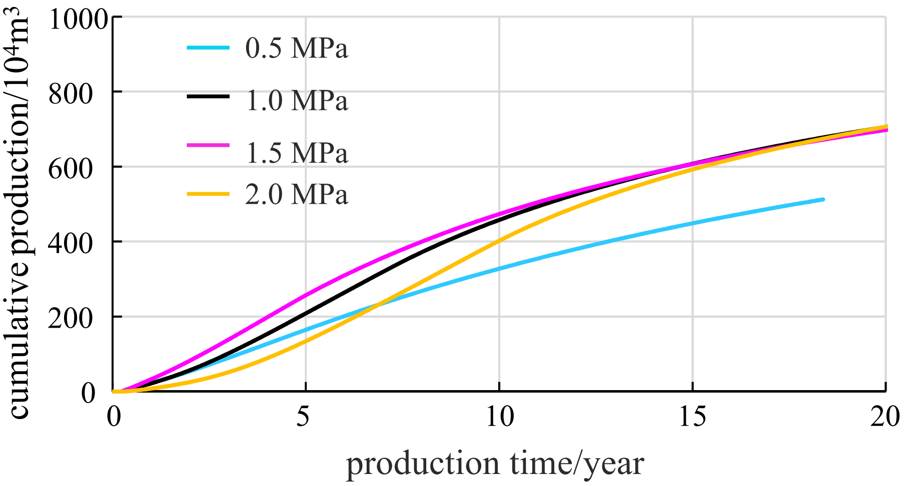

Figure 14. Cumulative gas production curves at different turning pressures.

Due to the unreasonable drainage and mining system, the coal seam is subjected to strong stress sensitivity, the artificial crack is closed, the cut seepage channel is compressed, and the permeability is reduced. In order to solve the problem of low production caused by the drainage and production system, it is suggested to use the plugging removal measures to increase production. At present, 12 secondary pressure cracking plugging measures have been tested (Figure 15), and 11 of the 12 measured wells have had stimulation effects. Secondary pressure cracking plugging can dredge the original seepage channel, and the effect is better for the low-production and low-efficiency wells caused by the drainage system. Therefore, in view of the low-production wells caused by the drainage system, it is recommended to adopt secondary pressure cracking plugging to increase production.

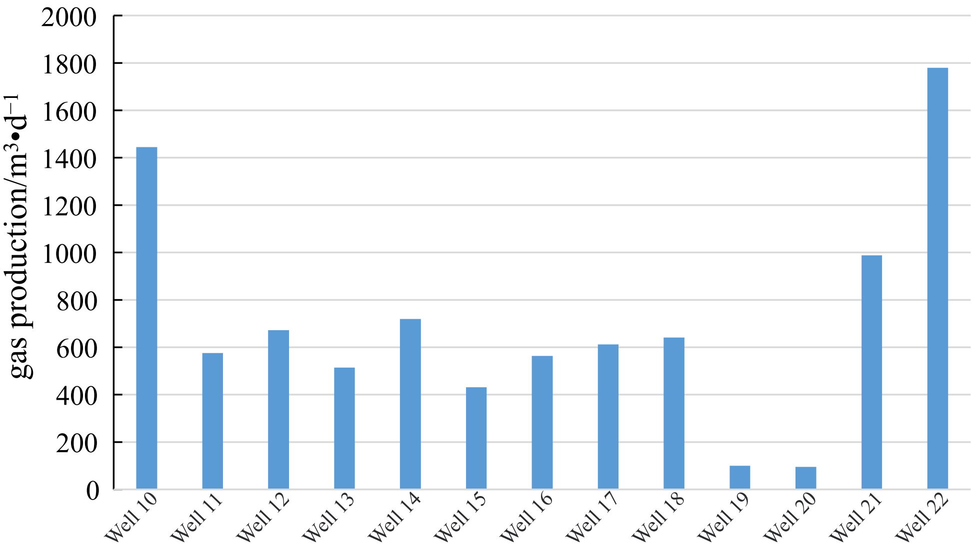

Figure 15. The block production system affects the effects of secondary pressure, fracture, and plugging.

5. Conclusions

1. The typical curve method can be used to directly judge whether the coalbed methane well is a low-yield and low-efficiency well, but it needs to average the typical curve. At the same time, on the basis of the typical average curve, combined with an economic evaluation and considering the production cost of a single well, we can further judge whether the low-yield and low-efficiency well has economic benefits.

2. The reasons for the low production and low efficiency of coalbed methane wells can be divided into three categories. The first category is geological reasons, including resource abundance, fault influence, and collapse column influence. The second reason is the impact of fracturing construction. The fracturing effect can be judged according to the type of fracturing construction curve so as to determine whether the gas production of coalbed methane wells is affected by the fracturing effect. The third factor is the drainage and production system, as the continuity of drainage and production mainly affects the production effect of gas wells, but the impact of drainage and production in block A is mainly reflected in the production system.
3. In the process of secondary fracturing, if the fracture length of the secondary fracture is consistent with that of primary fracture, then the fracturing fluid will extend in the original fracture and will not produce an obvious stimulation effect, and the length of the fracture after secondary fracturing should be increased by more than 30 m to achieve the stimulation effect.
4. In view of the reasons for the formation of low-production and low-efficiency wells, there are few measures for coalbed methane wells affected by geological factors, mainly deciding whether to close wells. Reservoir reconstruction measures such as large-scale secondary fracturing, temporary block diversion fracturing, and nitrogen foam fracturing can be adopted for wells affected by the fracturing effect. For wells affected by the drainage and production system, large-scale secondary fracturing can be adopted to dredge the original seepage channels and increase the gas production of coalbed methane wells.

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