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Full Length Article

Comprehensive judgment method of low production causes in tight gas reservoirs——Taking the LX gas reservoir in Ordos Basin as an example

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A B S T R A C T

The low production of tight gas reservoirs arises from complex and multifaceted causes, and elucidating these factors is crucial for guiding the formulation of effective stimulation strategies. Conventional analytical methods predominantly emphasize the role of individual factors, thereby lacking necessary systematic and integrative perspective to comprehensively reveal underlying mechanisms of poor well performance. To overcome these limitations, a comprehensive diagnostic approach is proposed to identify controlling factors of low production in multilayer tight gas reservoirs. Taking three typical cluster well groups of LX tight gas reservoirs in the Ordos Basin as examples, the causes for the low production of the gas wells were analyzed from different aspects by using geological, engineering, and developmental data after excluding the special reasons such as defects in drilling and completion process, reservoir water lock, and water flooding. The results show that the main causes for the low production of gas wells in LX reservoirs include fewer exploited gas layers, poor physical properties, poor fracturing and fracture making effects, and insufficient formation energy. In addition, corresponding treatment measures such as reperforation and refracturing were proposed. Finally, effects of the measures in the two low-yield wells where the reperforation was implemented were analyzed: the production and Tubing-head pressure increased significantly, and the low-yield wells were transformed into non-low-yield wells with good results. The results of the measures demonstrate the feasibility of the new method.

1. Introduction

China's onshore tight gas resources are estimated to be approximately 21.9×10^{12} m^3, widely distributed in basins such as the Ordos Basin, Sichuan Basin (Wei et al., 2024), and Junggar Basin (Pan et al., 2017), with significant potential for development. Tight gas reservoirs generally exhibit characteristics such as low porosity, low permeability, low storage capacity, and strong heterogeneity (Guo et al., 2018; Lu et al., 2018; Ma et al., 2024), and most tight gas wells achieve production through hydraulic fracturing, typically entering a low production period within 1–3 years. The causes of low production in tight gas wells are numerous and complex. Conducting research on the causes for low production in tight gas wells is crucial and meaningful as it allows for more targeted proposed remedial measures to improve the production capacity of low-yield wells.

Currently, there is limited research literature specifically

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addressing the causes of low production in gas wells. Gu et al. (2004) analyzed the causes of low production in gas wells in terms of sedimentary facies types and diagenetic processes, but did not take into account the influence of development and engineering factors on production capacity. Dong et al. (2024) investigated the mechanisms of wellbore blockage in the Linxing Gas Field and the stimulation effects of deblocking techniques on low-yield wells, but did not discuss the applicability of their findings to other gas fields. Tian et al. (2016) believed that liquid accumulation in the wellbore and pollution of the reservoir significantly reduced production capacity, leading to low gas well production. Li et al. (2022) argued that non-uniform water invasion could cause low production in gas wells. These scholars primarily focus on single categories of influencing factors to investigate the causes of low production in gas wells. However, there is no documented research that considers multiple categories of influencing factors simultaneously. This paper, focusing on the low-yield gas wells in the development of multi-layer tight gas reservoirs with cluster well patterns, comprehensively integrates geological, engineering, and development data to conduct a comparative analysis of low-yield and non-low-yield wells within the cluster well group. The study investigates the various causes for low production in gas wells and proposes corresponding remedial measures. The new method for analyzing the causes of low production in multi-layer tight gas wells proposed in this paper can clearly identify the primary causes of low production and provide directional measures for how to implement remedial measures in gas wells.

Through an analysis of the causes of low production in the LX tight gas reservoir, this method has been verified as applicable to tight gas reservoirs in the Ordos Basin. Moreover, it holds certain reference value for tight gas reservoirs in other regions, such as the Sichuan Basin. However, it should be noted that geological conditions and development strategies vary among different basins. For example, when applying this method to tight gas reservoirs in the Sichuan Basin, where edge and bottom water are more active, it is essential to fully account for the presence and dynamic characteristics of these water bodies and their impact on development performance. Therefore, the applicability of this research method in different regions requires further modification and adjustment in accordance with specific reservoir characteristics.

2. Methods

In the development of multi-layer tight gas reservoirs, some gas wells fail to reach the target gas production, resulting in low-yield wells. The potential causes of low production in low-yield wells in multi-layer tight gas reservoirs are diverse. From a geological perspective, these include poor reservoir porosity and permeability, low gas saturation, and small effective gas layer thickness (Hamd-Allah and Al-Ameri, 2023; Liu et al., 2022; Mo et al., 2019; Xiao et al., 2023). From an engineering perspective, these include defects in wellbore design and completion processes, suboptimal hydraulic fracturing execution, and formation damage caused by fracturing fluids (Zangqa et al., 2024). From a development perspective, these include significant depletion of formation energy, sand particle accumulation or blockage in the wellbore or tubing during development, edge or bottom water invasion leading to reservoir water-locking, and severe liquid accumulation in the wellbore (Liu et al., 2023; Miao and Zhong, 2021; J. Wang et al., 2020).

For multi-layer tight gas reservoirs low-yield gas wells, the specific causes of low production can be effectively identified by following the steps (Fig. 1).

Step 1: Identification of low-yield wells in multi-layer tight gas reservoirs

On a well group basis, the criteria for determining whether the current stable production rate is below the industrial target production rate is adopted to identify whether each production well in the well group is a low-yield well. The industrial target production rate is generally determined based on field experience and may vary among different reservoir management departments depending on their specific conditions.

Step 2: Data collection and processing for gas wells

Data collection and processing have been conducted from three aspects: geological, engineering, and development. Geological data primarily includes the distribution and activity evaluation results of edge and bottom water, as well as information on perforated and completed production intervals, such as the number of layers, effective thickness, porosity, permeability, and gas saturation. Engineering data mainly includes the evaluation results of wellbore design and completion process quality, along with hydraulic fracturing execution assessments, such as fracture half-length, fracture height, proppant volume, and fracturing fluid damage evaluation results. Production dynamic data primarily includes information on formation pressure, wellbore pressure, gas well production rate, cumulative production, and water production.

Step 3: Special causes analysis for low-yield gas wells in multi-layer tight gas reservoirs

Low production in multilayer tight gas reservoirs can generally be ascribed to two categories of factors. The first are general causes, which stem from inherent geological and engineering constraints, such as low porosity, poor permeability, insufficient gas saturation, and limited effectiveness of hydraulic fracturing. These conditions are widespread and systematically restrict production potential (Liu and Li, 2023). The second are special causes, which arise from wellbore design, completion practices, and operational measures. Examples include structural or completion defects, formation damage from fracturing fluids, sand deposition leading to plugging, and water intrusion causing water blocking, flooding, or severe liquid loading. Unlike the general causes, these issues are well-specific and highly variable. Usually, only a few wells encounter issues with defective wellbore design and completion processes. Additionally, most current operations utilize clean and non-damaging fracturing fluids (Liu et al., 2023; Zhang et al., 2020), and pre-fracturing fluid damage evaluations are commonly conducted. Therefore, the likelihood of formation damage caused by fracturing fluids is relatively low. Sand particle blockage in the wellbore or tubing may occur during development, particularly in cases where the sandstone is relatively loose. Reservoirs with highly active edge or bottom water are more prone to issues such as water-locking, water coning, and severe liquid accumulation in the wellbore.

When analyzing the causes of low production in multi-layer tight gas reservoirs, special causes should be prioritized for investigation. If one or more of these special causes are identified, targeted remedial measures should be proposed. For example: For issues related to wellbore design and completion process defects, options such as sidetracking or drilling new wells in adjacent areas may be considered (Z. Wang et al., 2020). For formation damage caused by fracturing fluids, re-selecting a new non-damaging fracturing fluid system and performing re-fracturing may be considered (Lai et al., 2017). For sand particle blockage in the wellbore or tubing, well intervention operations such as sand removal and sand bailing may be conducted (Pao et al., 2015; Joshi, D et al., 2022). For water-locking, water coning, and severe liquid accumulation in the wellbore, measures such as water-locking removal and water-free production processes may be implemented (Chen et al., 2020; Li et al., 2023). If no special causes are

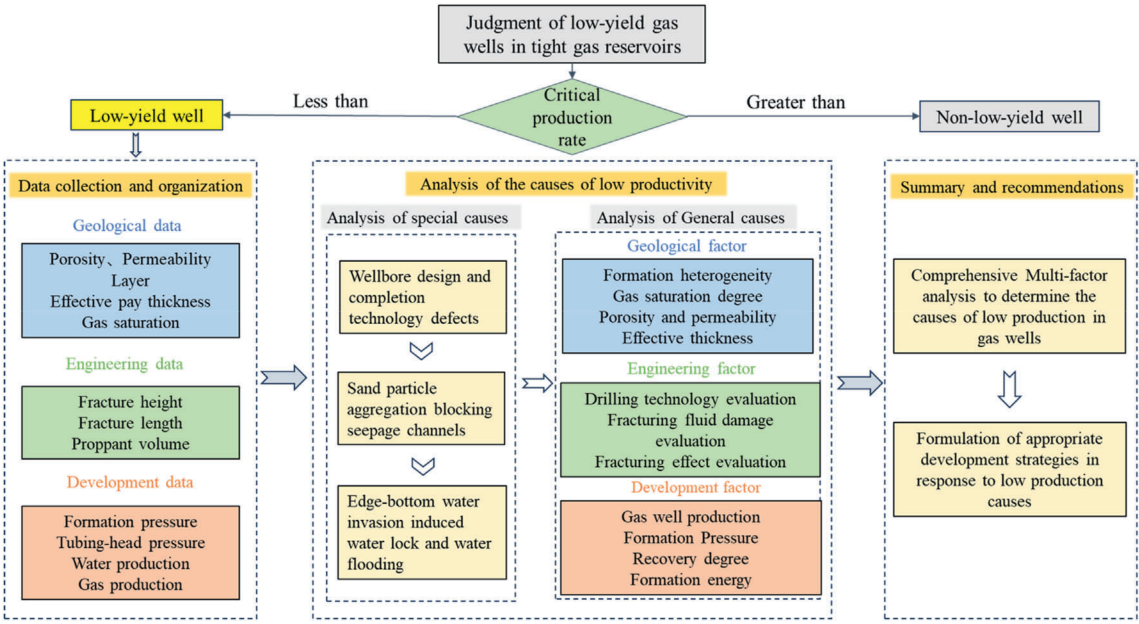

Fig. 1. Framework diagram for analyzing causes of low production of multilayer tight gas reservoirs.

identified, the analysis should then proceed to investigate one or more general causes of low production from geological, engineering, and development perspectives, following steps 4 to 7.

Step 4: Comparison and analysis of geological characteristic parameters among production wells in a well group

Within the well group, the reservoir properties of the perforation intervals in low-yield wells and non-low-yield wells are compared, and the differences in porosity, permeability, gas saturation, and effective thickness are analyzed to determine if the low production cause is attributed to geological factors. If the porosity, permeability, gas saturation, and effective thickness parameters of low-yield wells are significantly smaller than those of non-low-yield wells, the reservoir is considered to exhibit strong heterogeneity, and the low production cause is due to poor reservoir properties (Cheng et al., 2023). In such cases, it is necessary to investigate whether there are other potentially favorable layers that have not been perforated. If such layers exist, measures such as adding new perforation intervals in these layers can be considered for implementation. Due to the presence of multiple tight gas reservoir layers, different wells may have perforations in different intervals, and a single well may have multiple perforation intervals. For the purpose of comparison, the porosity, permeability, and gas saturation are taken as the weighted averages of the effective thicknesses of the perforated intervals, while the effective thickness is taken as the sum of the effective thicknesses of all perforated intervals. If all wells in the well group are low-yield wells, non-low-yield wells from adjacent well groups within the same block should be selected as comparison wells. In this step, regardless of whether the low production cause is due to poor reservoir properties, potential low production causes related to engineering and development should also be analyzed.

Step 5: Comparison and analysis of engineering characteristic parameters among production wells in a well group

Within the well group, for low-yield wells with single-layer fracturing, non-low-yield wells that have undergone overpressure fracturing in the same layer are selected as comparison wells. The fracture half-length, fracture height, and proppant quantity of the low-yield wells are sequentially compared with those of the comparison wells to determine if the low production cause is attributed to engineering factors. In the same layer, if the fracture characteristic parameters of the low-yield wells are significantly smaller than those of the comparison wells, it indicates that the low production cause is due to poor fracturing performance (Ostojic et al., 2012). For low-yield wells with multi-layer fracturing, each layer of the well should be compared separately with the corresponding layer of non-low-yield wells. In practice, adjacent wells with multi-layer fracturing may involve more complex fracturing scenarios, and specific cases should be analyzed individually.

Step 6: Comparison and analysis of development characteristic parameters among production wells in a well group

Based on the original formation pressure and the current formation pressure, the degree of formation energy depletion is calculated. Formation pressure is an important indicator for evaluating reservoir energy, and it is typically determined through pressure buildup tests. However, in tight gas reservoirs, conducting such tests requires extended time and incurs high costs. As a result, only a limited number of wells have undergone pressure buildup testing, and pressure monitoring data from different production stages are rarely available. Considering that the process of oil and gas flowing from the reservoir to the wellbore and then to the wellhead is continuous, formation pressure, bottomhole flowing pressure, and tubing-head pressure exhibit similar trends under the same production pressure differential conditions. Therefore, for tight gas wells where historical formation pressure data cannot be obtained, changes in tubing-head pressure can indirectly reflect the reservoir energy status. Combined with the current production rate and pressure decline situation, the gas well's energy supply condition is evaluated. If the current pressure and production rate are low, and the pressure and production rate have significantly decreased compared to initial production, it indicates that with increasing development period, the low-yield well's reservoir energy supply is insufficient, and the low production cause is related to development.

Step 7: Multifactor comprehensive analysis to determine underproduction causes of each low-yield gas well

In this study, the underlying causes of low production in multilayer tight gas wells were examined through comparative analysis. Since it is challenging to quantitatively determine the specific contribution of each individual factor, their effects were categorized into three levels: "negligible contribution," "moderate contribution," and "significant contribution." Based on these classifications, an integrated evaluation framework was established to systematically identify and analyze the dominant factors controlling well productivity.

3. Cause analysis of low-yield wells in LX tight reservoir

The LX tight gas reservoir is located in the transitional zone of the Jinxi flexure zone and the Ishan slope zone in the Ordos Basin (Fig. 2). The structural framework was primarily formed during the late Yanshanian tectonic movement and finalized in the middle stage of the Himalayan tectonic movement. On the eastern side, the reservoir is influenced by folding and faulting within the Jinxi flexure zone, where faults provided migration pathways for hydrocarbons and formed local structural traps. On the western side, under the gentle structural background of the Ishan slope zone, the reservoir exhibits wide areal distribution, with the development of low-amplitude nose-shaped and lithologic traps (Guo et al., 2021; Yang et al., 2013). This gas reservoir is characterized by ultra-low resource abundance, ultra-low porosity, ultra-low permeability, and strong heterogeneity, and is classified as a medium–low productivity reservoir. The main pay layers of this reservoir are primarily from Palaeozoic Carboniferous Benxi Formation, Permian Taiyuan Formation (1st and 2nd members (Tai1 Member and Tai2 Member)) and Shihezi Formation (1st to 8th members (He1 Member to He8 Member)), followed by Shanxi Formation and Shiqianfeng Formation (Yu et al., 2024). The reservoir has no edge-bottom water development. The development adopts a cluster well pattern, where a single well group consists of 1 main well and 5–7 cluster wells. The main well is a vertical well, while the cluster wells are directional wells with their wellbore trajectories in the vertical well section within the target gas-bearing interval.

The identification of low-yield wells is generally based on the relationship between the stable production rate of a single well and the industrial critical production rate. The critical production rate for defining a low-yield well is not a single technical indicator; rather, it is constrained by the geological and reservoir conditions of the gas reservoir, while also being influenced by engineering practices and the economic environment. It is therefore a dynamic and comprehensive threshold. A reasonable definition requires a balanced consideration of technical capacity, economic limits, and production dynamics. The criteria for critical production rates vary across different gas reservoirs. For example, in a certain development block of the LX tight gas reservoir, the reservoir management authority has set the identification criterion for low-yield wells as a stable single-well gas production rate of less than 7500 m^3/d, based on actual field production conditions. Three typical well groups are selected as examples to analyze the causes of low production in tight gas wells under three different scenarios: low-yield wells account for a small proportion, a moderate proportion, and all wells being low-yield wells (Fig. 3). The LXL well group consists of 1 main well and 7 cluster wells, with 2 low-yield wells, accounting for 25%. The LXM well group consists of 1 main well and 5 cluster wells, with 3 low-yield wells, accounting for 50%. The LXN well group consists of 1 main well and 5 cluster wells, with all 6 wells being low-yield wells. These three typical well groups are relatively far apart and are not adjacent well groups, located in different structural positions within the reservoir. The reservoir layers being developed and their properties differ significantly among these three well groups.

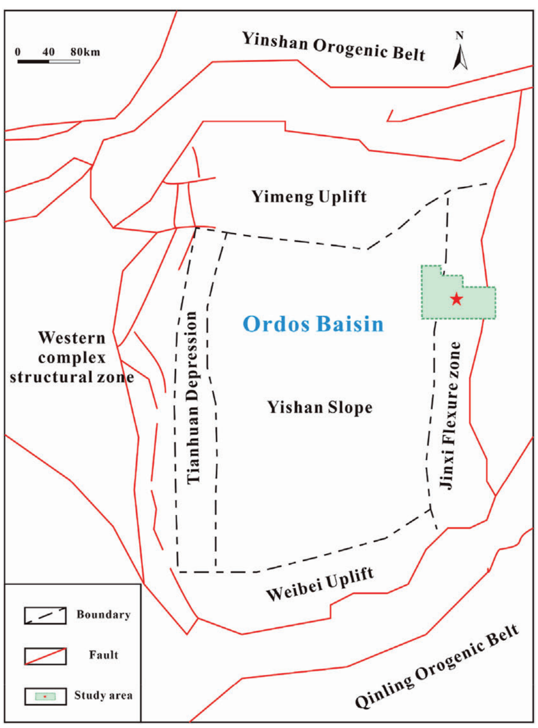

Fig. 2. Diagram of the division of tectonic units and the location of the study area in the Ordos Basin.

3.1. LXL well group

3.1.1. Data collection and organization

The LXL well group comprises a total of 8 wells, of which the LXL-1 is a vertical well and the rest are directional wells. This well group commenced production in October 2022, where LXL-4 and LXL-8 are classified as low-yield wells, producing 6301.6 m^3/d and 6391.8 m^3/d, respectively, as of February 2024. Since porosity, gas saturation, and permeability are fundamental macroscopic parameters for characterizing reservoir storage and flow capacity. At scales on the order of centimeters or larger, these parameters can be effectively represented by average values. In petroleum engineering practice, the weighted average method is a commonly employed data-processing technique, widely adopted by field engineers and technical personnel. For multilayer commingled wells, the average porosity, average permeability, and average saturation are calculated using an effective-thickness–weighted averaging method based on the individual sublayers. The weighting coefficient of each layer thickness is determined by the ratio of the effective thickness of the given layer to the sum of the effective thicknesses of all layers. The effective thickness of a single well is obtained as the sum of the effective thicknesses of all sublayers. The calculation formulas are as follows:

$$\phi = \sum_{j=1}^{n} w_j \phi_j \quad (1)$$

$$k = \sum_{j=1}^{n} w_j k_j \quad (2)$$

$$k_j = \sqrt[3]{k_{jx} \bullet k_{jy} \bullet k_{jz}} \quad (3)$$

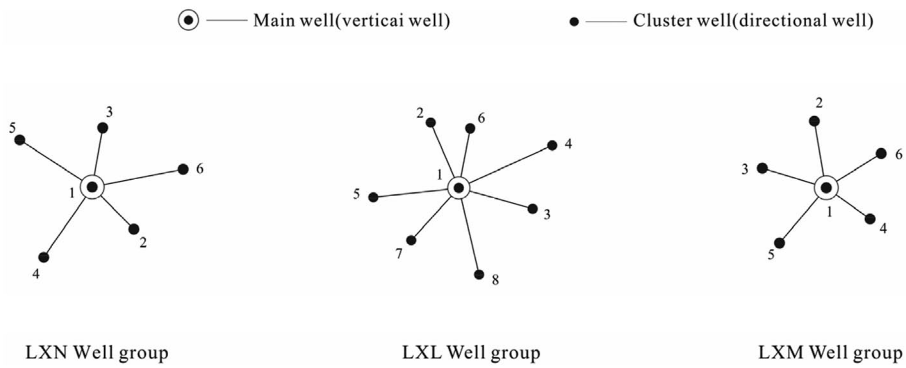

Fig. 3. Schematic plan of the relationship between the main well and cluster well configurations for the 3 typical well groups.

$$S_g = \sum_{j=1}^{n} w_j S_{gj} \tag{4}$$

$$h = \sum_{j=1}^{n} h_j \tag{5}$$

The formula for calculating the weighting coefficient is as follows:

$$w_j = \frac{h_j}{h} \tag{6}$$

Where ϕ is the average porosity; ϕ_j is porosity of the j layer; k is the average permeability, mD; k_j is the permeability of j layer, mD; k_{jx} is the permeability of j layer in the x-direction, mD; k_{jy} is the permeability of j layer in the y-direction, mD; k_{jz} is the permeability of j layer in the z-direction, mD; S_g is the average gas saturation; S_{gi} is the gas saturation of j layer; h is the effective thickness of a single well, m; h_j is the effective thickness of j layer, m; w_j is the weighting coefficient of j layer.

Production intervals, production rates, porosity, and effective thickness data for each well in this well group are shown in Table 1. Each well in the LXL well group underwent layered fracturing. Table 2 outlines the fracturing parameters for each well, including half-fracture length, fracture height, and sand addition rate.

3.1.2. Analysis of causes of low production

(1) Analysis of special causes

First, based on the evaluation results of drilling and completion quality, such as the cementation of LXL-4 and LXL-8 wells, as well as the fracturing fluid damage assessment, the special causes for

Table 1
Basic physical parameters of wells in the LXL Well group.

Well number	Production formation	q_g (m^3/d)	h (m)	ϕ (%)	k (mD)	S_g (%)	Remark
LXL-1	Tai1/He6/He1 Members	30079.1	19.5	12.68	1.91	55.11	Non-low-yield well
LXL-2	He1 Member	95733.8	10.2	13.20	2.81	58.99	Non-low-yield well
LXL-3	Tai1/He6 Members	12974.1	13.5	8.74	0.59	58.23	Non-low-yield well
LXL-4	Upper He8/He7 Members	6301.6	12.3	10.86	0.86	57.74	low-yield well
LXL-5	Upper He8/He7/He6 Members	28437.7	12.9	12.13	1.15	61.30	Non-low-yield well
LXL-6	Upper He8/He7/He5 Members	29184.6	23.7	13.13	1.89	59.30	Non-low-yield well
LXL-7	Tai1/He6/He1 Members	57881.9	19.1	11.73	1.33	58.04	Non-low-yield well
LXL-8	He1 Member	6391.8	8.0	9.3	0.5	54.3	low-yield well

Table 2
Fracture half-lengths, fracture heights, and sand additions for each fractured formation within the LXL well group.

Well number	fractured formation	X_f/m	H_f/m	V_s/m^3
LXL-1	Tai1 Member	133.2	33.5	40.0
	He6 Member	131.6	34.2	40.0
	He1 Member	129.7	35.1	39.9
LXL-2	He1 Member	149.5	38.2	50.2
LXL-3	Tai1 Member	133.4	33.7	40.2
	He6 Member	150.3	38.1	50.0
LXL-4	Upper He8 Member	131.9	34.7	40.1
	He7 Member	142.8	36.6	45.1
LXL-5	Upper He8 Member	135.5	31.4	40.1
	He7 Member + He6 Member	148.1	39.0	50.1
LXL-6	Upper He8 Member	150.1	38.7	50.1
	He7 Member	144.7	34.9	45.0
	He5 Member	134.6	32.3	40.0
LXL-7	Upper He8 Member	133.7	33.5	39.9
	He5 Member	143.1	35.9	45.1
	He1 Member	128.9	30.2	35.1
LXL-8	Tai1 Member	132.1	34.2	40.1
LXL	Mean	138.4 ± 7.8	35.0 ± 2.5	43 ± 4.7

low gas well production, such as defects in drilling and completion processes and secondary reservoir damage caused by fracturing fluids, can be ruled out. Second, according to the on-site proppant and wellbore fluid accumulation analysis during production operations, there is no significant sand or fluid accumulation at the bottom of the well, thus excluding special causes such as sand plugging in the wellbore and severe wellbore fluid accumulation. Furthermore, since the LX reservoir lacks edge-bottom water and the wells produce minimal water, special causes such as reservoir water locking and water coning can also be excluded. Therefore, after eliminating these special causes, the low production causes of LXL-4 and LXL-8 wells are further investigated in the order of geological, engineering, and developmental factors.

(2) Analysis of geological causes

Among six non-low-yield wells in the LXL well group, except for LXL-2 well which is single-layer production and LXL-3 well which is dual-layer production, the remaining four wells are three-layer production wells. The low-yield wells LXL-8 and LXL-4 are single-layer and dual-layer production wells, respectively. Therefore, the fewer open layers may be a possible cause for the low production of these two wells.

The producing layer of LXL-8 well is the Tai1 Member, with a gas production rate of 6391.8 m^3/d. Its thickness is 8 m, porosity is 9.3%, permeability is 0.5 mD, and gas saturation is 54.3%. For comparison, the non-low-yield LXL-2 well, which is also single-layer production, was selected. The producing layer of LXL-2 well is the He1 Member, with a gas production rate of 95733.8 m^3/d. Its thickness is 10.2 m, porosity is 13.20%, permeability is 2.81×10^{-3} μm^2, and gas saturation is 58.99%. The reservoir properties of LXL-2 well are significantly better than those of LXL-8 well (Fig. 4a): the thickness difference is 2.2 m, with a relative difference of 27.5%; the porosity difference is 3.9%, with a relative difference of 41.94%; the permeability difference is 2.31×10^{-3} μm^2, with a relative difference of 462%; the gas saturation difference is 4.69%, with a relative difference of 8.64%. Based on this analysis, poor reservoir properties are considered to be an important cause for the low production of LXL-8 well.

The producing layers of LXL-4 well are the upper He8 Member and He7 Member, with a gas production rate of 6301.6 m^3/d. The total thickness of the two members is 12.3 m, average porosity is 10.86%, average permeability is 0.86 mD, and average gas saturation is 57.74%. For comparison, the non-low-yield LXL-5 well, which has the closest total open layer thickness to LXL-4 well, was selected. The producing layers of LXL-5 well are the upper He8 Member, He7 Member, and He6 Member, with a gas production rate of 28437.7 m^3/d. Its total thickness is 12.9 m, porosity is 12.13%, permeability is 1.15 mD, and gas saturation is 61.30%. The reservoir properties of LXL-5 well are slightly better than those of LXL-4 well (Fig. 4b): the thickness difference is 0.6 m, with a relative difference of 4.88%; the porosity difference is 1.27%, with a relative difference of 11.69%; the permeability difference is 0.29 mD, with a relative difference of 33.72%; the gas saturation difference is 3.56%, with a relative difference of 6.17%. Based on this analysis, it is concluded that the low production of LXL-4 well is not caused by geological factors related to reservoir properties.

(3) Analysis of engineering causes

For the Tai1 Member of LXL-8 well, the fracture half-length is 132.1 m, the fracture height is 34.2 m, and the proppant volume is 40.1 m^3, and the sizes of all parameters fall within the error range (Fig. 5). A non-low-yield well in the same formation that underwent over-pressure fracturing was selected for comparison. The

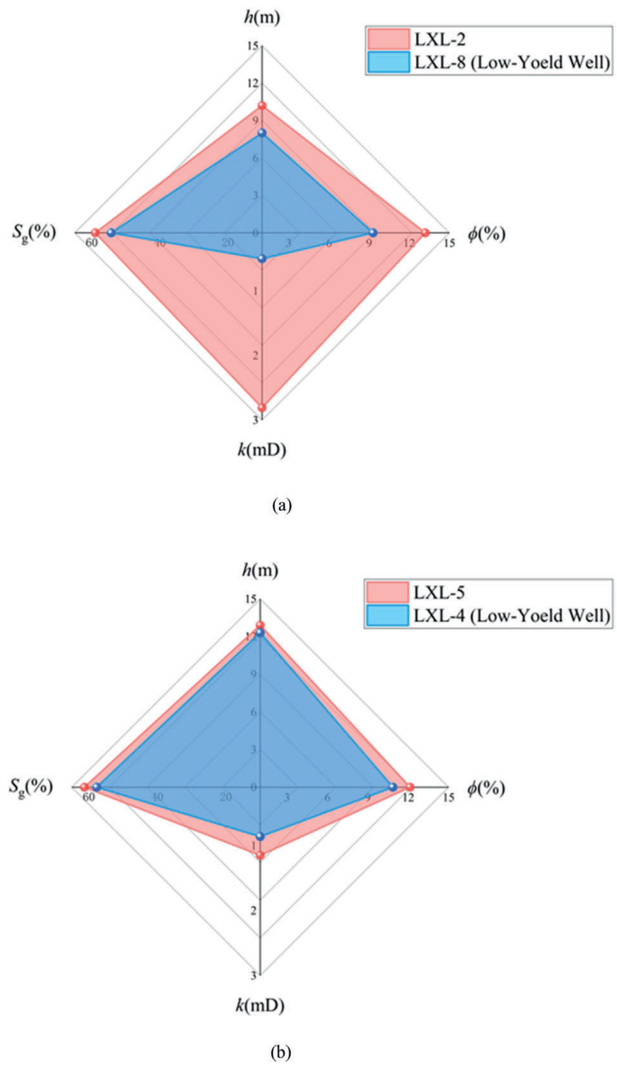

Fig. 4. Comparison of geological parameters between low-yield well and non-low-yield well in the LXL Well group.

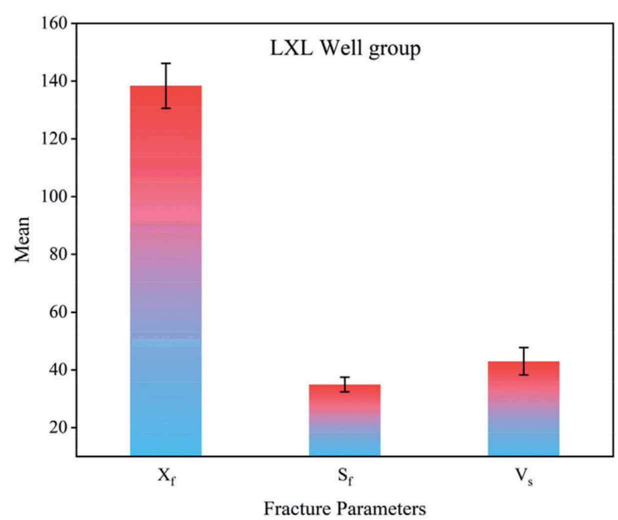

Fig. 5. Error analysis of hydraulic fracturing parameters in the LXL Well group.

comparison well, LXL-1 well, has a fracture half-length of 133.2 m, a fracture height of 33.5 m, and a proppant volume of 40 m^3. The Tail1 Member of LXL-1 well and LXL-8 well was compared: the fracture half-length differs by 1.1 m, with a relative difference of 0.83%; the fracture height and proppant volume of LXL-8 are slightly greater than those of LXL-1. Another comparison well, LXL-3, has a fracture half-length of 133.4 m, a fracture height of 33.7 m, and a proppant volume of 40.2 m^3. The Tai1 Member of LXL-3 well and LXL-8 well was compared: the fracture half-length differs by 1.3 m, with a relative difference of 0.98%; the fracture height of LXL-8 well is slightly larger than that of LXL-3 well; the proppant volume differs by 0.1 m^3, with a relative difference of 0.25%. The proppant volumes, fracture lengths, and fracture heights of the three wells in the Tai1 Member are extremely similar. Based on this analysis, it is concluded that the fracturing operation in LXL-8 well was effective, and engineering factors are not the cause of its low production.

For the upper He8 Member of LXL-4 well, the fracture half-length is 131.9 m, the fracture height is 34.7 m, and the proppant volume is 40.1 m^3. A non-low-yield well in the same formation that underwent over-pressure fracturing was selected for comparison. The comparison well, LXL-5 well, has a fracture half-length of 135.5 m, a fracture height of 31.4 m, and a proppant volume of 40.1 m^3. The upper He8 Member of LXL-5 well and LXL-4 well was compared: the fracture half-length differs by 3.6 m, with a relative difference of 2.73%; the fracture height of LXL-4 is slightly larger than that of LXL-5 well; the proppant volumes are identical. Another comparison well, LXL-7 well, has a fracture half-length of 133.7 m, a fracture height of 33.5 m, and a proppant volume of 39.9 m^3. The upper He8 Member of LXL-7 well and LXL-4 well was compared: the fracture half-length differs by 1.8 m, with a relative difference of 1.36%; the fracture height and proppant volume of LXL-4 well are slightly larger than those of LXL-7 well. The proppant volumes, fracture lengths, and fracture heights of the three wells in the upper He8 Member are extremely similar. Based on this analysis, it is concluded that the fracturing operation in the upper He8 Member of LXL-4 well was effective.

For the He7 Member of LXL-4 well, the fracture half-length is 142.8 m, the fracture height is 36.6 m, and the proppant volume is 45.1 m^3. Within the well group, the only non-low-yield well that underwent over-pressure fracturing in the He7 Member is LXL-6, which has a fracture half-length of 144.7 m, a fracture height of 34.9 m, and a proppant volume of 45.1 m^3. The He7 Member of LXL-6 well LXL-4 well was compared: the fracture half-length differs by 1.9 m, with a relative difference of 1.33%; the fracture height of LXL-4 is slightly larger than that of LXL-6; the proppant volumes are identical. Based on this analysis, it is concluded that the fracturing operation in the He7 Member of LXL-4 well was effective. Therefore, engineering factors are not the cause of the low production in LXL-4 well.

(4) Analysis of development causes

Due to the lack of formation pressure data from pressure recovery tests conducted during historical production processes of LXL, LXM, and LXN well groups, it is not possible to directly use formation pressure to analyze the energy status of the reservoir. Therefore, the variation in the tubing-head pressure data from each well can be used as an indirect parameter to analyze and assess the current level of reservoir energy maintenance.

The low-yield LXL-4 well commenced production on October 17, 2022. Its initial tubing-head pressure was 11.8 MPa. Throughout the production process, the tubing-head pressure consistently decreased, dropping to 3.4 MPa by February 16, 2024, representing a pressure decline of 71.19% (Fig. 6a). The initial production rate of the well was 36389.5 m^3/d, which declined rapidly in the early stage. By

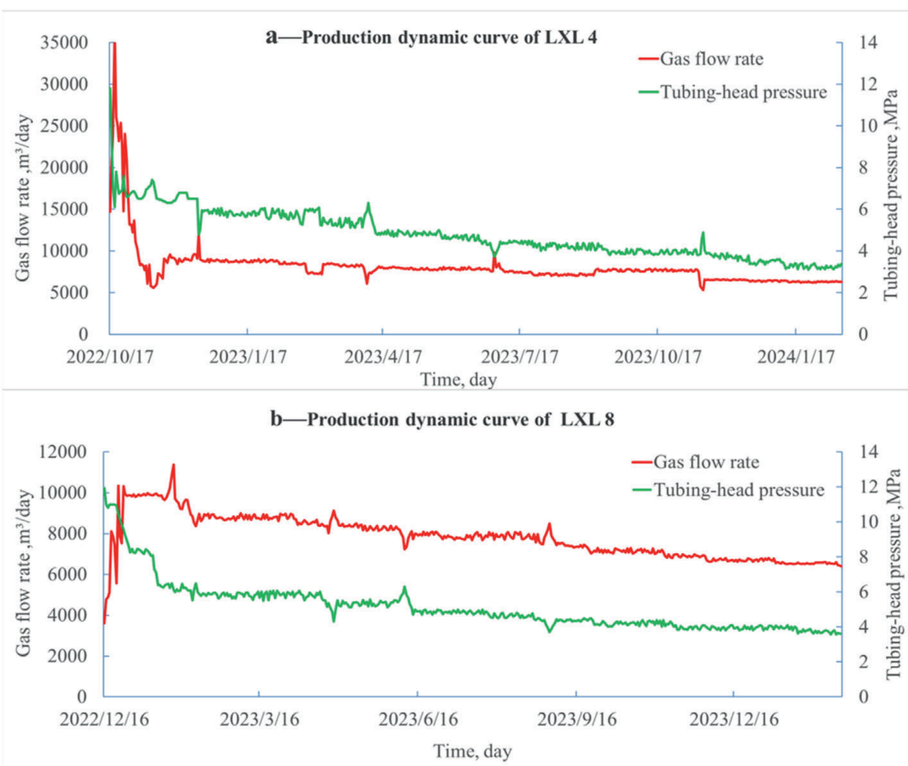

Fig. 6. Production and pressure versus time curves for low-yield wells in the LXL well group.

November 28, 2022, the production rate had dropped to 9062.7 m^3/d. Subsequently, the production rate continued to decrease gradually, reaching 7500 m^3/d by July 9, 2023, and further decreasing to 6301.6 m^3/d by February 16, 2024, representing an 82.68% reduction compared to the initial production rate. The well has been producing at a rate below 7500 m^3/d continuously for seven months. Currently, there is a significant shortfall in gas layer energy supply, leading to low well productivity.

The low-yield LXL-8 well commenced production on October 17, 2022. Its initial tubing-head pressure was 12 MPa. Throughout the production process, the tubing-head pressure consistently decreased, dropping to 3.6 MPa by February 16, 2024, representing a pressure decline of 70% (Fig. 6b). The initial production rate of the well was 11379.6 m^3/d, which declined rapidly in the early stage. By February 9, 2023, the production rate had dropped to 8746.7 m^3/d. Subsequently, the production rate continued to decrease gradually, reaching 7500 m^3/d by September 8, 2023, and further decreasing to 6391.8 m^3/d by February 16, 2024, representing a 43.83% reduction compared to the initial production rate. The well has been producing at a rate below 7500 m^3/d continuously for five months. Currently, there is a significant shortfall in gas layer energy supply, leading to low well production.

The low production cause of well LXL-4 is due to insufficient gas layer energy. For well LXL-8, the low production is attributed to both unfavorable gas properties and insufficient energy (Table 3). Considering that fracture construction and fracture effectiveness were successful for both low-yield wells (LXL-4 and LXL-8), and noting that LXL-8 is currently only producing from the Tai1 Member while LXL-4 is only producing from the upper He8 Member and the He7 Member, a comparison with other non-low-yield wells in the same well group that are producing from three intervals suggests that further potential intervals should be identified. Based on the comprehensive log interpretation results of LXL-4 and LXL-8 wells, it is recommended to carry out additional perforation operations in other promising intervals to enhance gas well production.

3.2. LXM well group

3.2.1. Data collection and organization

The LXM well group comprises a total of 6 wells, of which the LXM-1 well is a vertical well, and the remaining wells are directional wells. This well group commenced production in July 2022, with LXM-1, LXM-2, and LXM-6 wells identified as low-yield wells. As of March 2024, their production rates are 5109.3 m^3/d, 6276.4 m^3/d, and 6613.7 m^3/d. The production formation, production rate, porosity, and effective thickness of each well in this well group are listed in Table 4. Key fracturing parameters for each well in the LXM well group, including fracture half-length, fracture height, and proppant quantity, are shown in Table 5.

3.2.2. Analysis of causes of low production

(1) Analysis of special causes

Similar to the LXL well group, it is first possible to rule out special causes of low gas well production, such as drilling and

Table 5
Fracture half-lengths, fracture heights, and sand additions for each fractured formation within the LXM well group.

Well number	fractured formation	X_f/m	H_f/m	V_s/m^3
LXM-1	Tai1 Member	128.9	29.7	35.0
	Upper He8 Member	103.2	24.7	25.0
LXM-2	Tai1 Member	128.0	30.5	35.0
LXM-3	Lower He8 Member	133.1	33.5	40.2
	Upper He8 Member	134.2	32.7	40.0
LXM-4	Upper He8 Member	128.4	30.2	35.0
LXM-5	Lower He8 Member	134.3	32.9	40.0
LXM-6	Upper He8 Member	133.8	33.7	40.1
LXM	Mean	127.2 ± 10.9	30.6 ± 3.0	35.7 ± 5.4

Note: Well LXM-4 was only hydraulically fractured in the upper He8 Member, and Well LXM-5 was only hydraulically fractured in the lower He8 Member.

Table 3
Summary of the causes of low productivity in the LXL well group.

Factor	Comparison parameters	LXL-4			Impact factors	LXL-8			Impact factors
Geological factors		LXL-4	LXL-5	Relative difference	★	LXL-8	LXL-2	Relative difference	★★★
	h (m)	12.3	12.9	4.88%		8	10.2	27.5%	
	Φ (%)	10.86	12.13	11.69%		9.3	13.2	41.94%	
	K (mD)	0.86	1.15	33.72%		0.5	2.81	462%	
	S_g (%)	57.74	61.3	6.17%		54.3	58.99	8.64%	
Engineering factors		Relative difference			★	Relative difference			★
		LXL-5	LXL-7	LXL-6		LXL-1		LXL-3	
	X_f (m)	2.73%	1.36%	1.33%		0.83%		0.98%	
	H_f (m)	9.51%	3.46%	3.83%		2.05%		1.46%	
	V_s (m^3)	0%	0.50%	0%		0.25%		0.25%	
Development factors		Initial	Present	Decline rate	★★★	Initial	Present	Decline rate	★★
	p_t (MPa)	11.8	3.4	71.19%		12	3.6	70%	
	q_g (m^3/d)	36389.5	6301.6	82.68%		11379.6	6391.8	43.83%	

Note: The relative difference is defined as the absolute value of the parameter difference between low-yield and non–low-yield wells, normalized by the parameter value of the low-yield well. Contribution levels are denoted as follows: ★ = negligible contribution; ★★ = moderate contribution; ★★★ = significant contribution.

Table 4
Basic physical parameters of wells in the LXM well group.

Well number	Production formation	q_g (m^3/d)	h (m)	ϕ (%)	k (mD)	S_g (%)	Remark
LXM-1	Tai1/Upper He8 Member	5109.3	9.9	10.2	0.95	54.62	low-yield well
LXM-2	Tai1 Member	6276.4	4.1	11.4	1.09	53.90	low-yield well
LXM-3	Lower/Upper He8 Member	8961.1	4.6	11.8	1.05	54.88	Non-low-yield well
LXM-4	Upper He8/Tai1 Member	9133.5	10.0	10.8	0.91	55.55	Non-low-yield well
LXM-5	Lower He8/He4 Member	8016.8	4.8	13.3	1.95	54.64	Non-low-yield well
LXM-6	Upper He8 Member	6613.7	9.2	7.9	0.54	54.8	low-yield well

completion process defects, formation damage by fracturing fluids, sand particles blocking the tubing, severe liquid accumulation at the bottom of the well, formation water locking, and water coning. After excluding these special causes, the low production causes of LXM-1, LXM-2, and LXM-6 wells are further investigated in the order of geological, engineering, and development factors.

(2) Analysis of geological causes

In the LXM well group, three non-low-yield wells are all dual-layer production wells, while the low-yield LXM-2 well and LXM-6 well are single-layer production wells. LXM-1 well is a dual-layer production well. Therefore, opening fewer layers may be a possible cause for the low production of LXM-2 and LXM-6 wells. In addition, the low-yield LXM-1 well and the non-low-yield LXM-4 well from the LXM well group were selected for comparison. LXM-1 well is a vertical well, whereas LXM-4 well is a directional well. Both wells are located in the Tai1 Member and the upper He8 Member, and both produce from two commingled layers. The two wells exhibit very similar permeability, porosity, and effective thickness, with the only notable difference being in gas saturation. However, the production of LXM-4 well is significantly higher than that of LXM-1 well. It is therefore inferred that the low production of LXM-1 well may be attributed to its relatively lower gas saturation and its well type being vertical. Under comparable conditions, directional wells generally yield higher production than vertical wells.

The LXM-2 well targets the Tai 1 Member with a gas production rate of 6276.4 m^3/d. The layer has a thickness of 4.1 m, a porosity of 11.4%, a permeability of 1.09 mD, and a gas saturation of 53.9%. For comparison, the non-low-yield LXM-3 well, which has the closest open gas layer thickness to LXM-2 well, was selected. The LXM-3 well targets the upper He8 Member and lower He8 Member with a gas production rate of 8961.1 m^3/d. The layer has a thickness of 4.6 m, a porosity of 11.84%, a permeability of 1.05 mD, and a gas saturation of 54.88%. The reservoir properties of LXM-3 well are slightly better than those of LXM-2 well (Fig. 7a): the thickness differs by 0.5 m, with a relative difference of 12.2%; porosity differs by 0.44%, with a relative difference of 3.86%; permeability of LXM-2 well is slightly higher than that of LXM-3 well, and gas saturation differs by 0.98%, with a relative difference of 1.82%. Based on this analysis, the low production of LXM-2 well is not attributed to geological causes related to reservoir properties.

The LXM-6 well targets the upper He8 Member with a gas production rate of 6613.7 m^3/d. The layer has a thickness of 9.2 m, a porosity of 7.9%, a permeability of 0.54 mD, and a gas saturation of 54.8%. For comparison, the non-low-yield LXM-4 well, which has the closest open gas layer thickness to LXM-6 well, was selected. The LXM-4 well targets the Tai 1 Member and upper He8 Member with a gas production rate of 9133.5 m^3/d. The layer has a thickness of 10 m, a porosity of 10.88%, a permeability of 0.91 mD, and a gas saturation of 55.55%. The reservoir properties of LXM-4 well are significantly better than those of LXM-6 well (Fig. 7b): the thickness differs by 0.8 m, with a relative difference of 8.70%; porosity differs by 2.98%, with a relative difference of 37.72%; permeability differs by 0.37 mD, with a relative difference of 68.52%, and gas saturation differs by 0.75%, with a relative difference of 1.37%. Based on this analysis, poor reservoir properties are identified as a key factor contributing to the low production of LXM-6 well.

The LXM-1 well targets the Tai 1 Member and upper He8 Member with a gas production rate of 5109.3 m^3/d. The total thickness of the two layers is 9.9 m, with an average porosity of 10.22%, an average permeability of 0.95 mD, and an average gas saturation of 54.62%. For comparison, the non-low-yield LXM-4 well, which has the closest open gas layer thickness to LXM-1 well,

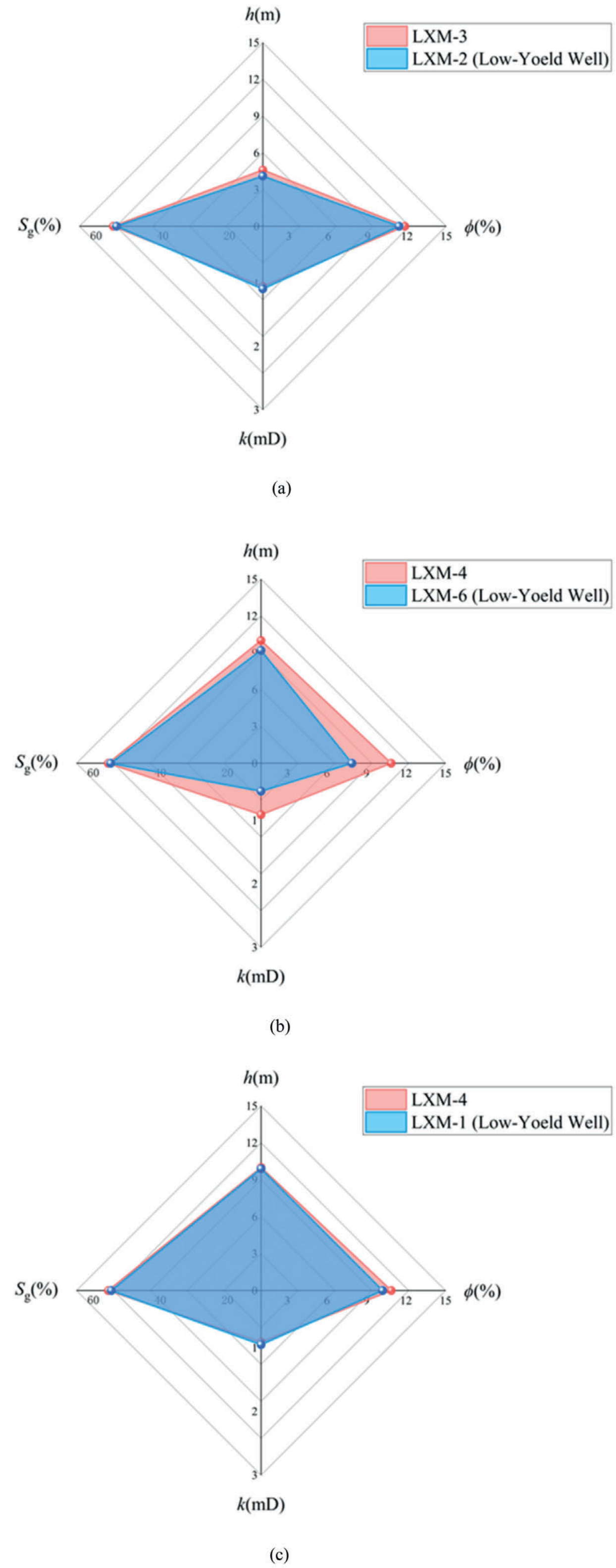

Fig. 7. Comparison of geological parameters between low-yield well and non-low-yield well in the LXM well group.

was selected. The LXM-4 well targets the Tai 1 Member and upper He8 Member with a gas production rate of 9133.5 m^3/d. The layer has a thickness of 10 m, a porosity of 10.88%, a permeability of 0.91 mD, and a gas saturation of 55.55%. The reservoir properties of LXM-4 well are slightly better than those of LXM-1 well (Fig. 7c): the thickness differs by 0.1 m, with a relative difference of 1.01%; porosity differs by 0.66%, with a relative difference of 6.46%; the permeability of LXM-1 well is slightly higher than that of LXM-4 well, and gas saturation differs by 0.93%, with a relative difference of 1.70%. Based on this analysis, the low production of LXM-1 well is not attributed to geological causes related to reservoir properties.

(3) Analysis of engineering causes

For the Tai1 Member of LXM-2 well, the fracture half-length is 128 m, the fracture height is 30.5 m, and the proppant volume is 35 m^3, and the sizes of all parameters fall within the error range (Fig. 8). Since there are no non-low-yield wells in the LXM well group that have undergone over-pressure fracturing in the Tai1 Member, a non-low-yield well with a similar proppant volume to the Tai1 Member of LXM-2 well was selected as the comparable well. For the LXM-4 well in the upper He8 Member, the fracture half-length is 128.4 m, the fracture height is 30.2 m, and the proppant volume is 35 m^3. The Tai1 Member of LXM-2 well and the upper He8 Member of LXM-4 well was compared: the fracture half-length differs by 0.4 m, with a relative difference of 0.31%; the fracture height of LXM-2 well is slightly larger than that of LXM-4 well; and both wells have the same proppant volume. Based on this analysis, it can be concluded that the fracturing operation for the Tai1 Member of LXM-2 well is effective, and the low production of this well is not due to engineering causes.

For the upper He8 Member of LXM-6 well, the fracture half-length is 133.8 m, the fracture height is 33.7 m, and the proppant volume is 40.1 m^3. A non-low-yield well that has undergone fracturing in the upper He8 Member was selected as the comparable well. The comparable well, LXL-3 well, has a fracture half-length of 134.2 m, a fracture height of 32.7 m, and a proppant volume of 40.0 m^3. The upper He8 Member of LXM-6 well and LXL-3 well was compared: the fracture half-length differs by 0.4 m, with a relative difference of 0.30%; the fracture height and proppant volume of LXM-6 well are slightly larger than those of LXL-3 well. Based on this analysis, it can be concluded that the fracturing operation for the LXM-6 well is effective, and the low production of this well is not due to engineering causes.

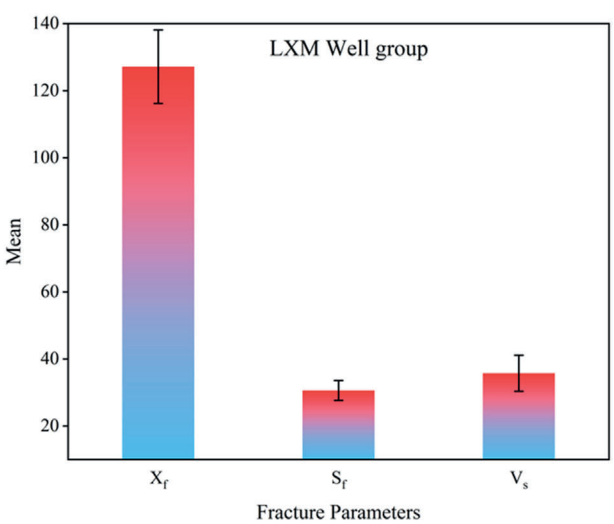

Fig. 8. Error analysis of hydraulic fracturing parameters in the LXM Well group.

For the Tai1 Member of LXM-1 well, the fracture half-length is 128.9 m, the fracture height is 29.7 m, and the proppant volume is 35 m^3. Since there are no non-low-yield wells in the LXM well group that have undergone over-pressure fracturing in the Tai1 Member, a non-low-yield well with a similar proppant volume to the Tai1 Member of LXM-1 well was selected as the comparable well. The comparable well, LXM-4 well, has a fracture half-length of 128.4 m, a fracture height of 30.2 m, and a proppant volume of 35 m^3 in the upper He8 Member. The Tai1 Member of LXM-1 well and the upper He8 Member of LXM-4 well was compared: the fracture half-length differs by 0.5 m, with a relative difference of 0.39%; the fracture height differs by 0.5 m, with a relative difference of 1.68%; and both wells have the same proppant volume. Based on this analysis, it can be concluded that the fracturing operation for the Tai1 Member of the LXM-1 well is effective.

For the upper He8 Member of LXM-1 well, the fracture half-length is 103.2 m, the fracture height is 24.7 m, and the proppant volume is 25 m^3. A non-low-yield well that has undergone fracturing in the upper He8 Member was selected as the comparable well. The comparable well, LXL-3 well, has a fracture half-length of 134.2 m, a fracture height of 32.7 m, and a proppant volume of 40.0 m^3. The He8 Member of LXM-1 well and LXL-3 well was compared: the fracture half-length differs by 31 m, with a relative difference of 30.04%; the fracture height differs by 8 m, with a relative difference of 32.39%; and the proppant volume differs by 15 m^3, with a relative difference of 60%. Based on this analysis, it is concluded that the fracturing operation for the upper He8 Member in the LXM-1 well is relatively ineffective. Therefore, the poor fracturing effect in the upper He8 Member in the LXM-1 well is a significant cause for its low production.

(4) Analysis of development causes

The low-yield LXM-1 well began production on July 17, 2022. The initial tubing-head pressure was 10.8 MPa with a production rate of 8573.2 m^3/d. The well was shut in on August 24, 2022, and reopened on October 18, 2022, with a tubing-head pressure of 13.4 MPa and a production rate of 23102.4 m^3/d. As of March 3, 2024, the tubing-head pressure dropped to 3.1 MPa, indicating a decrease of 76.87% (Fig. 9a). Subsequently, the production rate decreased rapidly within a short period. By November 21, 2022, the production rate fell to 9712.3 m^3/d. After a brief fluctuation, the production rate gradually declined, reaching 7500 m^3/d by August 18, 2023. As of March 3, 2024, the production rate further decreased to 5109.3 m^3/d, representing a 77.88% reduction from the initial production rate after reopening. This well has been producing continuously below 7500 m^3/d for 7 months, and currently, there is an evident shortfall in energy supply from the gas layer, resulting in low well productivity.

The low-yield LXM-2 well started production on September 7, 2022, with an initial tubing-head pressure of 13.2 MPa. Throughout its production process, the tubing-head pressure consistently declined. As of March 3, 2024, the tubing-head pressure dropped to 3 MPa, a decrease of 77.27% (Fig. 9b). The initial production rate was 9838.4 m^3/d, with significant fluctuations in the early period. By November 23, 2022, the production rate fell to 8787.3 m^3/d. Subsequently, the production rate decreased gradually, reaching 7500 m^3/d by July 8, 2023. As of March 3, 2024, the production rate further decreased to 6276.4 m^3/d, representing a 36.21% reduction from the initial production rate. This well has been producing continuously below 7500 m^3/d for 8 months, and currently, there is an evident shortfall in energy supply from the gas layer, resulting in low well productivity.

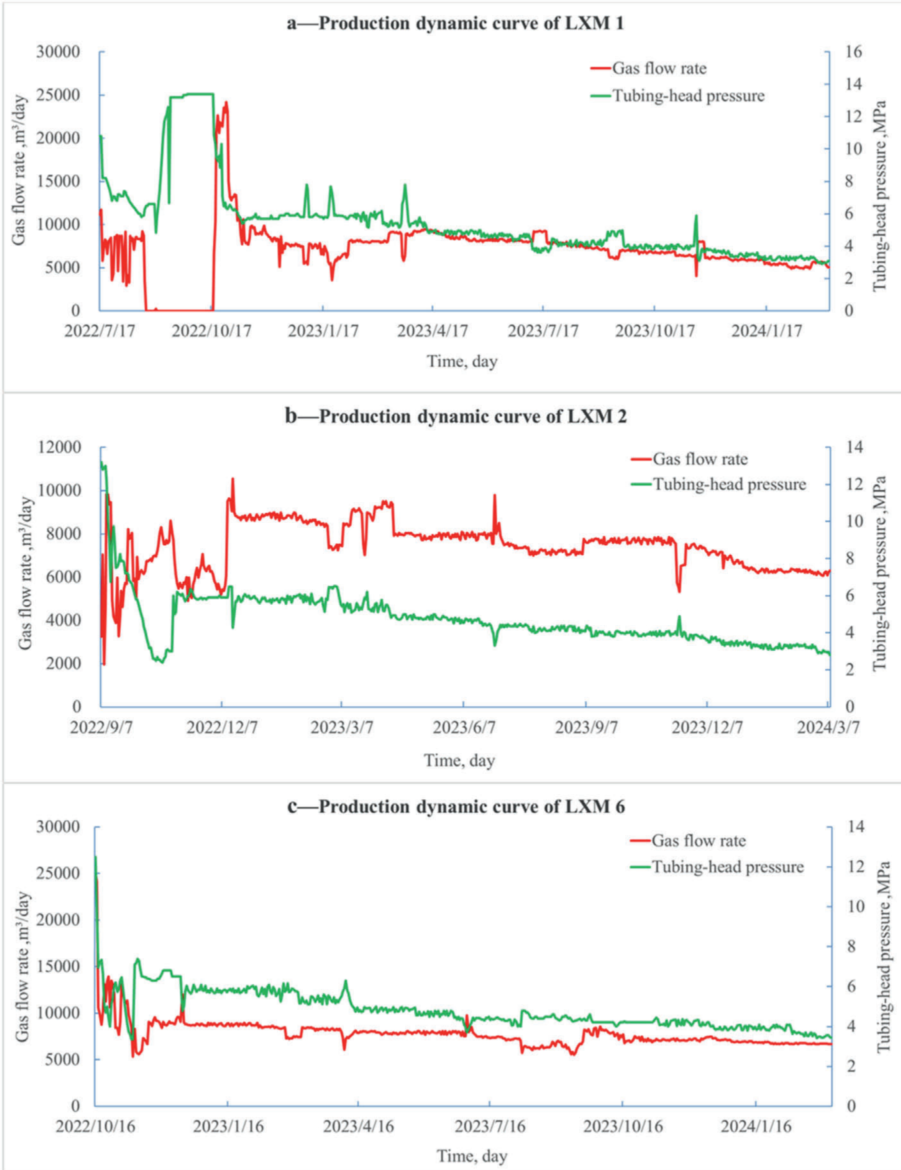

Fig. 9. Production and pressure versus time curves for low-yield wells in the LXM well group.

The low-yield LXM-6 well began production on October 16, 2022, with an initial tubing-head pressure of 12.5 MPa. Throughout its production process, the tubing-head pressure consistently declined. As of March 3, 2024, the tubing-head pressure dropped to 3.5 MPa, a decrease of 72% (Fig. 9c). The initial production rate was 25158.9 m^3/d, with a rapid decline in the early period. By November 27, 2022, the production rate fell to 9158.4 m^3/d. Subsequently, the production rate decreased gradually, reaching 7500 m^3/d by July 10, 2023. As of March 3, 2024, the production rate further decreased to 6613.7 m^3/d, representing a 73.71% reduction from the initial production rate. This well has been producing continuously below 7500 m^3/d for 8 months, and currently, there is an evident shortfall in energy supply from the gas layer, resulting in low well productivity.

The low production of LXM-1 well is attributed to insufficient reservoir energy and poor fracture generation effectiveness during the fracturing operation in the upper He8 Member. It is recommended to implement a re-fracturing operation in the upper He8 Member to enhance fracture network development and improve gas well productivity. The low production of Well LXM-2 is primarily caused by insufficient reservoir energy. For LXM-6 well, the low production results from poor reservoir quality and inadequate energy (Table 6). Given that both LXM-2 well and LXM-6 well exhibit effective fracture generation from previous fracturing operations and are currently under single-layer production, it is advised to identify additional potential intervals based on comprehensive well log interpretation results and perform additional perforation operations to boost gas well productivity.

3.3. LXN well group

3.3.1. Data collection and organization

The LXN well group consists of 6 wells, of which the LXN-1 well is a vertical well and the remaining wells are directional wells. This well group was put into production in December 2021. All six wells in the LXN well group are low-yield wells, with a daily production rate of less than 7500 m^3/d as of March 2024. The production formation, production rate, porosity, and effective thickness of each well in this well group are listed in Table 7. Within the LXN well group, the upper and lower He8 Member in well LXN-2 are

Table 6
Summary of the causes of low productivity in the LXM well group.

Factor	Comparison parameters	LXM-1			Impact factors	LXM-2			Impact factors	LXM-6			Impact factors
Geological factors		LXM-1	LXM-4	Relative difference	★	LXM-2	LXM-3	Relative difference	★	LXM-6	LXM-4	Relative difference	★★★
	h (m)	9.9	10	1.01%		4.1	4.6	12.2%		9.2	10	8.7%	
	Φ (%)	10.22	10.88	6.46%		11.4	11.84	3.86%		7.9	10.88	37.72%	
	K (mD)	0.95	0.91	4.21%		1.09	1.05	3.67%		0.54	0.91	68.52%	
	S_g (%)	54.62	55.55	1.7%		53.9	54.88	0.98%		54.8	55.55	1.37%	
Engineering factors		Relative difference			★★★	Relative difference			★	Relative difference			★
		LXM-3		LXM-4		LXM-4				LXM-3			
	X_f (m)	30.04%		0.39%		0.31%				0.3%			
	H_f (m)	32.39%		1.68%		0.98%				2.97%			
	V_s (m^3)	60%		0%		0%				0.25%			
Development factors		Initial	Present	Decline rate	★★★	Initial	Present	Decline rate	★★	Initial	Present	Decline rate	★★★
	p_t (MPa)	13.4	3.1	76.87%		13.2	3	77.27%		12.5	3.5	72%	
	q_g (m^3/d)	23102.4	5109.3	77.88%		9838.4	6276.4	36.21%		25158.9	6613.7	73.71%	

Table 7
Basic physical parameters of wells in the LXN well group.

Well number	Production formation	q_g (m^3/d)	h (m)	ϕ (%)	k (mD)	S_g (%)	Remark
LXN-1	Lower/Upper He8 Member	5976.4	5.1	9.74	0.49	56.47	low-yield well
LXN-2	Lower/Upper He8 Member	5693.4	4.1	8.47	0.33	51.88	low-yield well
LXN-3	Lower/Upper He8 Member	5881.7	7.7	9.07	0.55	57.51	low-yield well
LXN-4	Lower He8 Member	5793.8	7.0	9.4	0.5	54.1	low-yield well
LXN-5	Lower/Upper He8 Member	6641.3	15.6	9.76	0.51	57.81	low-yield well
LXN-6	Lower/Upper He8 Member	4899.7	5.7	8.43	0.36	52.44	low-yield well

dual-layer fractured, while the remaining wells are segmented fractured. Data on fracture half-length, fracture height, and proppant volume for each well in the well group are shown in Table 8.

3.3.2. Analysis of causes of low production

(1) Analysis of special causes

For the LXN well group, some special causes of low gas production can be ruled out, such as drilling and completion process defects, secondary reservoir damage from fracturing fluid, sand particle blockage in the tubing, severe liquid accumulation at the bottom of the well, reservoir water lock, and water coning. After excluding these special causes, the low production causes for each well in the LXN well group were investigated in the order of geological, engineering, and development factors.

(2) Analysis of geological causes

Table 8
Fracture half-lengths, fracture heights, and sand additions for each fractured formation within the LXN well group.

Well number	fractured formation	X_f/m	H_f/m	V_s/m^3
LXN-1	Lower He8 Member	132.5	34.0	40.0
	Upper He8 Member	135.3	33.8	40.0
LXN-2	Lower He8 Member +Upper He8 Member	132.1	31.7	39.8
LXN-3	Lower He8 Member	133.2	33.9	40.0
	Upper He8 Member	134.7	31.5	40.0
LXN-4	Lower He8 Member	134.1	32.6	40.1
LXN-5	Lower He8 Member	135.4	31.5	40.1
	Upper He8 Member	134.0	32.7	40.1
LXN-6	Lower He8 Member	135.9	33.3	40.1
	He7 Member	132.1	34.1	40.0
LXN	Mean	133.9 ± 1.4	32.9 ± 1.1	40.0 ± 0.1

All six wells in the LXN well group are low-yield wells. Except for the LXN-4 well, which is a single-layer production well, the remaining five wells are dual-layer commingled wells. The main production intervals in this well group are primarily in the upper and lower He8 Member, while the upper He8 Member and He Member in the LXN-6 well.

The porosity of the six wells in the LXN well group ranges from 8.43% to 9.76%, with permeability ranging from 0.33 to 0.55 mD, and gas saturation ranging from 51.88% to 57.81%. Both porosity and permeability fall within a relatively narrow range, indicating that the overall reservoir properties of the six wells in the LXN well group are poor. Since there are no non-low-yield wells in the well group, a comparison analysis was conducted using the LXN-5 well, which has the highest current production, and the LXK-1 well, a non-low-yield well in an adjacent well group. The LXK-1

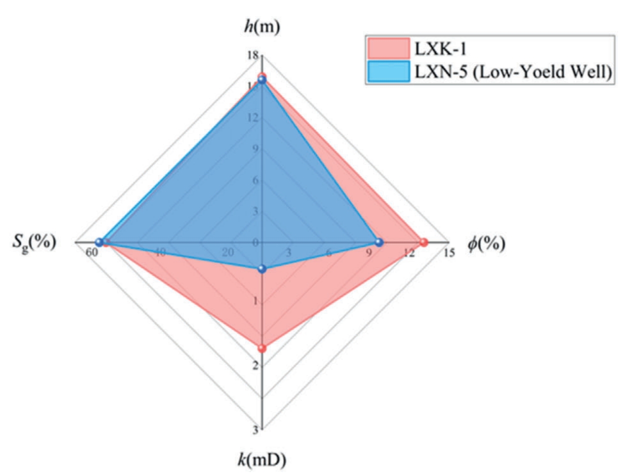

Fig. 10. Comparison of geological parameters between low-yield well and non-low-yield well in the LXN well group.

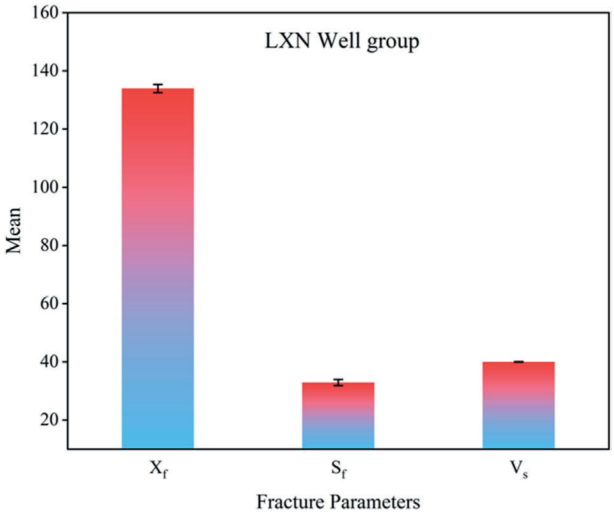

Fig. 11. Error analysis of hydraulic fracturing parameters in the LXN Well group.

well has a total thickness of 15.9 m, an average porosity of 13.11%, an average permeability of 1.74 mD, and an average gas saturation of 55.88%. The reservoir properties of LXK-1 well are significantly better than those of LXN-5 well (Fig. 10): thickness difference is 0.3 m, with a relative difference of 1.92%; porosity difference is 3.35%, with a relative difference of 34.32%; permeability difference is 1.23 mD, with a relative difference of 241.18%; gas saturation of LXN-5 well is slightly better than that of LXK-1 well. Based on this analysis, poor reservoir properties are identified as a key cause of low production in the LXN-5 well and the entire well group.

(3) Analysis of engineering causes

The fracture of the upper He8 Member in the LXN-5 well has a half-length of 134 m, a height of 32.7 m, and a sand volume of 40.1 m^3, and the values of all parameters fall within the error range (Fig. 11). In comparison, the fracture of the upper He8 Member in the LXK-1 well has a half-length of 133.2 m, a height of 33.5 m, and a sand volume of 40.1 m^3. The fracture of the upper He8 Member in the LXN-5 well and the LXK-1 wells: the half-length of LXN-5 well is slightly better than that of LXK-1 well; the fracture height differs by 0.8 m, with a relative difference of 2.45%; both have identical sand volumes. Based on this analysis, the fracture creation in the Upper He8 segment of LXN-5 well is effective.

The fracture of the lower He8 Member in the LXN-5 well has a half-length of 135.4 m, a height of 31.5 m, and a sand volume of 40.1 m^3. In comparison, the fracture of the lower He8 Member in the LXK-1 well has a half-length of 135.2 m, a height of 32.5 m, and a sand volume of 40.1 m^3. The fracture of the lower He8 Member in the LXN-5 well and the LXK-1 well was compared: the half-length of LXN-5 well is slightly better than that of LXK-1 well; the fracture height differs by 1 m, with a relative difference of 3.17%; both have identical sand volumes. Based on this analysis, the fracture creation in the lower He8 Member of LXN-5 well is effective. Therefore, the low production of LXN-5 well and the entire well group is not caused by engineering .

(4) Analysis of development causes

For the situation where all wells in the LXN well group are low-yield wells, the production rate and tubing-head pressure changes in each well within the group are similar. Therefore, LXN-1 and LXN-6 wells was used as examples to conduct low-production cause analysis. The production dynamic curves for LXN-1 and LXN-6 wells are shown in Fig. 12a and b.

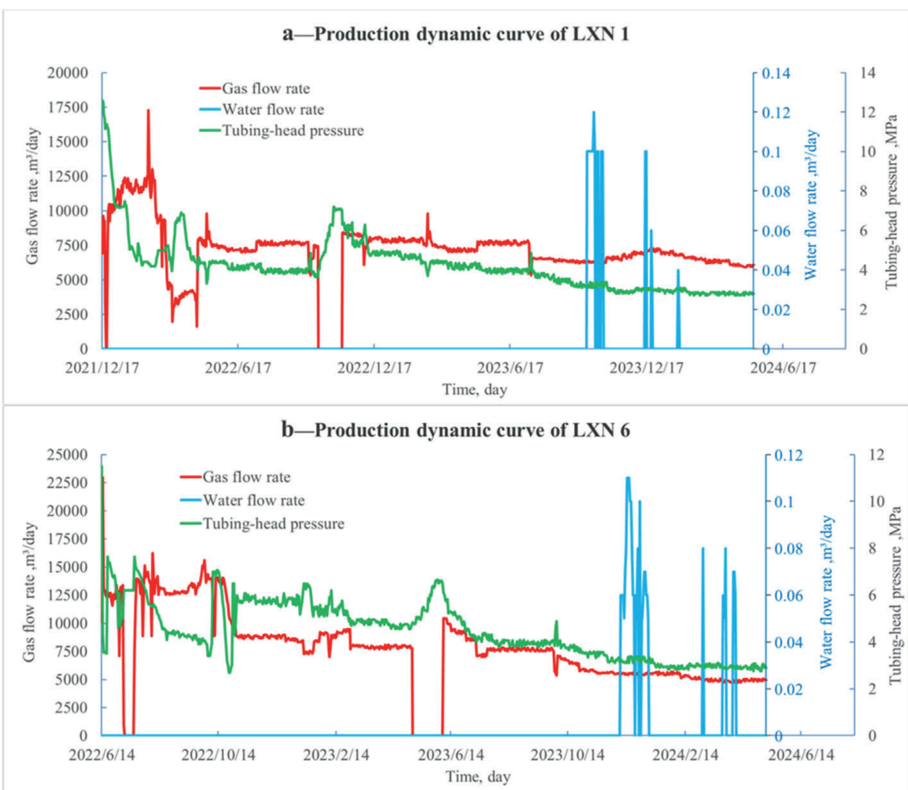

Fig. 12. Production and pressure versus time curves for low-yield wells in the LXN well group.

The LXN-1 well commenced production on December 17, 2021. The initial tubing-head pressure was 12.6 MPa, but both tubing-head pressure and production rate continuously declined during production. As of May 8, 2024, the tubing-head pressure dropped to 2.8 MPa, a decrease of 77.77%. The initial production rate of this well was 17273.6 m^3/d, with significant fluctuations in early production. By May 5, 2022, the production rate decreased to 7442.7 m^3/d, followed by a gradual decline. The well was shut in on October 3, 2023, and resumed production on November 4, 2023, with a tubing-head pressure of 7.1 MPa and a production rate of 8418.9 m^3/d. By March 7, 2024, the production rate fell to 7500 m^3/d, and as of May 8, 2024, the production rate was 5976.4 m^3/d, representing a 65.4% decrease compared to the initial production rate. This well has been producing continuously below 7500 m^3/d for 14 months. Currently, the gas layer's energy supply is significantly insufficient, resulting in low well productivity.

The LXN-6 well commenced production on June 14, 2022. The initial tubing-head pressure was 11.5 MPa, but both tubing-head pressure and production rate continuously declined during production. As of May 8, 2024, the tubing-head pressure dropped to 2.7 MPa, a decrease of 76.52%. The initial production rate of this well was 16215.7 m^3/d, with significant fluctuations in early production. By November 14, 2022, the production rate decreased to 8803.4 m^3/d, followed by a gradual decline. The well was shut in on May 5, 2023, and resumed production on June 6, 2023, with a tubing-head pressure of 6.7 MPa and a production rate of 9864.3 m^3/d. By July 10, 2023, the production rate fell to 7500 m^3/d, and as of May 8, 2024, the production rate was 4899.7 m^3/d, representing a 69.78% decrease compared to the initial production rate. This well has been producing continuously below 7500 m^3/d for 10 months. Currently, the gas layer's energy supply is significantly insufficient, resulting in low well productivity.

The cause for the low production of all wells in the LXN well group is the poor gas layer properties and insufficient energy (Table 9). Considering that the fracturing renovation effect of all wells in this well group is relatively good, there is no need to carry out repeated fracturing renovation operations. Additionally, since this well group is located on the edge of the gas reservoir, the gas

Table 9
Summary of the causes of low productivity in the LXN well group.

Factor	Comparison parameters	LXN Well group						Impact factors
Geological factors		LXN-5		LXK-1		Relative difference		★★★
	h (m)	15.6		15.9		1.92%		
	Φ (%)	9.76		13.11		34.32%		
	K (mD)	0.51		1.74		241.18%		
	S_g (%)	57.81		55.88		3.34%		
Engineering factors		Relative difference						★
		LXK-1			LXK-1			
	X_f (m)	0.6%			0.15%			
	H_f (m)	2.45%			3.17%			
	V_s (m^3)	0%			0%			
Development factors		Initial		Present		Decline rate		★★★
		LXN-1	LXN-6	LXN-1	LXN-6	LXN-1	LXN-6	
	p_t (MPa)	12.6	11.5	2.8	2.7	77.77%	76.52%	
	q_g (m^3/d)	17273.6	16215.7	5976.4	4899.7	65.4%	69.78%	

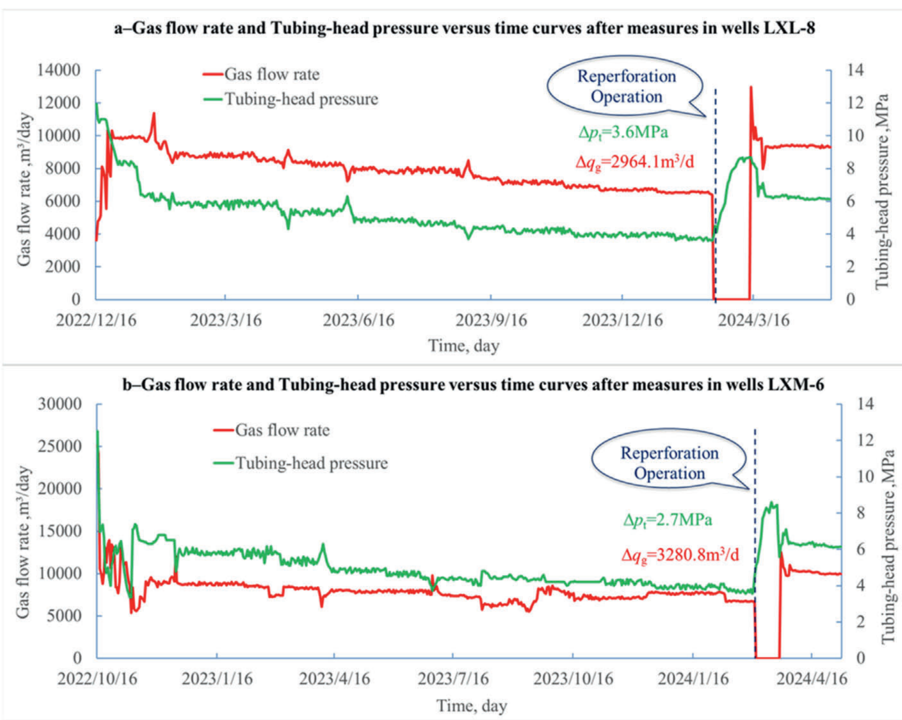

Fig. 13. Production and pressure versus time curves after measures in wells LXL-8 and LXM-6.

layer properties of each well and each section are poor, and the potential for increasing production by adding new perforation sections is small. Therefore, it is recommended to list this well group as an abandoned potential exploration object.

4. Examples ofeffectiveness measures for low-yield tight gas wells

Based on suggestions for low-yield well measures proposed in this study, currently, only the perforation operations were carried out on LXL-8 and LXM-6 wells. These operations significantly improved the single-well production capacity. According to the gas production rate criterion of 7500 m^3/d, these two wells are now transformed into non-low-yield wells, and the measures is proven to be very effective. However, the perforation and re-fracturing operations recommended for other low-yield wells have not yet been implemented in the field, and thus their effectiveness cannot be demonstrated. Performance analysis of measures for LXL-8 and LXM-6 wells as follows:

The perforation operation for LXL-8 well was conducted on February 17, 2024, targeting He1 Member at a vertical depth of 1589.0–1592.9 m, with a thickness of 3.9 m, a porosity of 8.9%, a permeability of 0.43 mD, and a gas saturation of 55.1%. After the perforation, the well was put back into production on March 14, 2024, achieving a stable gas production rate of 9355.9 m^3/d and a tubing-head pressure of 6.2 MPa, as shown in Fig. 13a. Compared to the pre-perforation production, the gas production increased by 2964.1 m^3/d, representing a growth rate of 46.37%, while the tubing-head pressure increased by 3.6 MPa, achieving a 100% rise.

The perforation operation for LXM-6 well was carried out on March 4, 2024, targeting He1 Member at a vertical depth of 1586.9–1591.2 m, with a thickness of 4.3 m, a porosity of 7.3%, a permeability of 0.49 mD, and a gas saturation of 54.5%. Following the perforation, the well resumed production on March 23, 2024, producing a stable gas volume of 9894.5 m^3/d and a tubing-head pressure of 6.2 MPa, as shown in Fig. 13b. Compared to the pre-perforation production, the gas output increased by 3280.8 m^3/d, with a growth rate of 49.61%, and the tubing-head pressure increased by 2.7 MPa, showing a growth of 77.14%.

5. Conclusion

(1) A systematic method for analyzing causes of low-yield wells in multiple tight gas reservoirs was established. By analyzing characteristic parameters from geological, engineering, and development perspectives, the specific causes for low-yield wells can be effectively identified, enabling targeted measures to be proposed for their treatment.
(2) The method proposed in this study is not only applicable to tight gas reservoirs in the Ordos Basin, but also provides a valuable reference for other tight gas reservoirs, such as those in the Sichuan Basin; however, appropriate modifications should be made in accordance with specific geological and development characteristics when analyzing special influencing factors.
(3) For LX gas reservoir in Ordos Basin, the proportion of low-yield wells in the LXL, LXM, and LXN well groups accounts for 25%, 50%, and 100% of total number of wells within each group, respectively. The main causes of low production are poor reservoir properties, ineffective fracturing, and insufficient gas layer energy. To improve the production capacity of low-yield wells, recommendations for supplemental perforation operations in new potential layers were proposed for wells such as LXL-4, LXL-8, LXM-2, and LXM-6. Refracturing measures were suggested for upper He8 Member in LXM-1 well. For the LXN well group, it was recommended to abandon further development.
(4) Utilizing the proposed measures, additional layer perforation operations were carried out in two low-yield wells. . After taking the measures, the gas well production rates both exceeded 7500 m^3/d, indicating excellent measure effects: for LXL-8 well, a new 3.9-m perforation layer was added in He1 Member, compared to pre-measure values, the gas well production increased by 2964.1 m^3/d, representing a growth rate of 46.37%; for LXM-6 well, a new 4.3-m perforation layer was added in He1 Member, compared to pre-measure values, the gas well production increased by 3280.8 m^3/d, representing a growth rate of 49.61%.

CRediT authorship contribution statement

Ren-Shi Nie: Writing – review & editing. **Peidong Qiu:** Writing – original draft. **Jingcheng Liu:** Methodology. **Bin Liu:** Investigation. **Zhangxin Chen:** Methodology. **Cong Lu:** Project administration. **Fan-Hui Zeng:** Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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