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Geological Characteristics and Development Techniques for Carbonate Gas Reservoir with Weathering Crust Formation in Ordos Basin, China

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Abstract: The carbonate gas reservoir is one of the most important gas formation types; it comprises a large proportion of the global gas reserves and the annual gas production rate. However, a carbonate reservoir with weathering crust formation is rare, and it is of significant interest to illustrate the geological characteristics of this kind of formation and present the emerging problems and solution measures that have arisen during its exploitation. Therefore, in this research, a typical carbonate gas reservoir with weathering crust formation that is located in Ordos Basin, China, was comprehensively studied. In terms of formation geology, for this reservoir, the distribution area is broad and there are multiple gas-bearing layers with low abundance and strong heterogeneity, which have led to large differences in gas well production performance. Some areas in this reservoir are rich in water, which seriously affects gas well production. Regarding production dynamics, the main production areas in this gas reservoir have been stable on a scale of 5.5 billion cubic meters for more than a decade, and the peripheral area has been continually evaluated to improve production capacity. Nevertheless, after decades of exploration and development, the main areas of this reservoir are faced with several problems, including an unclear groove distribution, an unbalanced exploitation degree, low formation pressure, and increases in intermittent gas wells. To deal with these problems and maintain the stability of gas reservoir production, a series of technologies have been presented. In addition, several strategies have been proposed to solve issues that have emerged during the exploration and exploitation of peripheral reservoir areas, such as low-quality formation, unclear ancient land and complex formation-water distribution. These development measures employed in the carbonate gas reservoir with weathering crust formation in the Ordos Basin will surely provide some guidance for the efficient exploitation of similar reservoirs in other basins all over the world.

Keywords: Ordos Basin; carbonate gas reservoir; weathering crust formation; geological characteristics; development technologies

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1. Introduction

Carbonate reservoirs play an important role in the global oil and gas industry. They comprise about 72% of global oil and gas reserves, and nearly 60% of global oil and gas production is produced from carbonate reservoirs [1–4]. In China, carbonate reservoirs comprise nearly 30% of natural gas reserves and 20% of gross gas production, and they have an important position in the supplement of natural gas. There are three basins in China that have large-scale carbonate reservoirs: the Tarim Basin (e.g., Tazhong and Lunnan), the Sichuan Basin (e.g., Gaoshiti, Moxi, Eastern Sichuan, Longgang, Yuanba, and Puguang), and the Ordos Basin (e.g., Jingbian and Gaoqiao). Globally, basins with giant carbonate gas reservoirs include the Persian Gulf Basin (e.g., North Field, Pars South, and Northwest Dome), the Pre-Caspian Basin (Astrakhan and Karachaganak), and the Zagros basin (Rag-E-Safid) [2]. These carbonate gas reservoirs can be divided into four categories depending on formation type: the fractured-vuggy reservoir, reef flat reservoir, bedded dolomite reservoir, and weathering crust reservoir [5–10]. The first three reservoirs are found all over the world and have been studied sufficiently, but the weathering crust carbonate reservoir is raw and has not been deeply investigated. Therefore, in this research, we studied the geological characteristics and optimal development strategies for a typical carbonate gas reservoir with weathering crust formation. This study can provide some insights into the exploration and development of similar carbonate gas reservoirs, such as the tight carbonate reservoirs in the north of Iraq, which possess Turonian–Campanian Kometan formations with low porosity and permeability [11].

Structures for weathering crust formation can be qualitatively separated according to color, mineral features, core properties, and other chemical indicators [12–16]. There are two main division schemes for this kind of formation: one identifies different layers, such as iron crust, fracture, lamination, and sandy weathering layers, and the other scheme identifies layers with different kinds of weathering zones, such as severely, weakly, and slightly weathered zones [13,16]. To date, many investigators have conducted studies regarding different kinds of formations with weathered crust features. Tian et al. [17] proposed a multi-layer artificial intelligence workflow to map the seismic attributes and represent the dissolution values of volcanic weathered crust formations. Zhu et al. [18] analyzed the vertical structure characteristics of granite weathering crusts for reservoirs in the western segment of the northern belt of Dongying Sag, Bohai Bay Basin, China, which possesses sandstone formations. Sidorova et al. [19] reported that the widespread weathering crust of crystalline basements can be used to study the mineral formation process of ancient weathering crust, though they did not study formation characteristics. However, these studies mainly focused on volcanic or sandstone reservoirs with weathering crust formation, and there has been a lack of the research regarding carbonate reservoirs.

There have been many geologic studies of the targeted gas reservoir, Jingbian gas field. Influenced by environmental variation at the end of the Middle Ordovician, the Ordos Basin was uplifted by the Caledonian movement and experienced 130–150 million years of weathering and erosion. In this period, the topography of the Jingbian platform was a large karst slope, in which the western area was higher than the eastern area and the surface water flowed from west to east. During this period, the effects of supergene leachate karsts were strong, which led to the formation of dendrite erosion grooves. In addition, the continuous replenishment of atmospheric and acidic aquifers caused the expansion of micro-cracks, solution pores, and intergranular solution pores, thus leading to the formation of large-area and layered area with porphyritic and honeycomb solution pores, as well as intensive weathering fractures and mechanical crusting fractures [20–22]. To determine the rock type, sedimentary characteristics, and environments of subsections 1 and 2 of member 5 in the Majiagou Formation, Xu et al. [23] distinguished sedimentary microfacies via geological laboratory analysis. The origins and gas sources of Ordovician paleo-weathering crust reservoirs can be determined with geochemical gas evidence, such as the carbon isotope reversal for the Ordos Basin [24,25]. To reconstruct the paleo-geomorphology of the weathering crust from the end of the Ordovician in the eastern part of the Ordos Basin, Wei et al. [26] studied paleo-geomorphic characteristics, the thickness of residual strata, and paleo-karsts. Li et.al [27] found that gases were accumulated in stratigraphic traps related to karst paleo-geomorphology and lithologic traps associated with the late diagenetic features of carbonate rocks. On the other hand, to study production dynamic in the Ordos Basin, Zhang et al. [28,29] used productivity testing in tandem with pressure build-up data and the “one point method” to estimate well productivity in the initial stages. Zhang et al. [30] and Yan et al. [31] analyzed the decline law of wellhead pressure under a constant production rate via geological modelling, numerical simulations, and gas reservoir engineering. Geologic investigations, well-logging, water production performance analysis, and the study of formation-water components and formation-water layer distribution have been used to determine the origins of the water produced in the Ordos Basin, and the produced water wells can be divided into four categories [32,33].

This comprehensive review of studies on the reservoir of interest (Jingbian gas field) clearly demonstrates that although many investigators have studied the geological characteristics and production performance of this reservoir, there is little understanding of its overall geologic features and development technologies. Most researchers have focused on one aspect, such as gas sources, sedimentary accumulation, gas well production behavior, and formation-water distribution. Therefore, the authors of this study describe the geological characteristics of this reservoir in general and then present the problems and solution strategies that have emerged during the exploration and development process. The innovations for this research mainly lie in the presentation of optimal exploitation technologies for the peripheral area based on comprehensive illustrations of the geology characteristics and encountered problems for this area, which have generally been ignored in previous studies. This study will be a significant reference for the efficient development of carbonate reservoirs in the Ordos Basin and similar gas reservoirs around the world.

2. Background of Gas Reservoir

The Jingbian gas field is a lower Paleozoic carbonate reservoir in the Ordos Basin, which is the first supergiant carbonate gas field in China. This reservoir is a typical weathering crust reservoir that is a part of the Changqing oil and gas field. The Ordos Basin is located in western North China Craton. Tectonic units are more stable in the central area than the margin areas. The Ordos Basin uplifts in the south and north margins and thrusts from west to east, which leads to the rise of the east margin. The whole basin can be subdivided into six tectonic units: Yimeng uplift, Weibei uplift, Jinxi flexing belt, western margin thrust belt, Yishan slop, and Tianhuan depression, as shown in Figure 1. Note that Yishan slop is the most significant tectonic unit for hydrocarbon accumulation. Lower Paleozoic carbonates in the Ordos Basin mainly were developed in the Cambrian and Ordovician periods. The Ordovician Majiagou Formation in the middle-east of the basin is the most important gas-bearing interval; it consists of six lithologic members, with member 1 at the bottom. Members 1, 3 and 5 of the Majiagou Formation are composed of dolomite with gypsum and salt rock. Members 2, 4, and 4 of the Majiagou Formation are composed of dolomite and limestone. Member 5 of the Majiagou Formation can be divided into 10 sub-members, starting from the top, among which sub-members 1, 2, and 4 are principal producing formations in the Jingbian weathering crust gas field and sub-members 5–10 comprise the gas reservoir formed by dolomite. The discovery of the Jingbian gas field suggested good development prospects for marine carbonate reservoir in the Ordos Basin and prompted the search for a large-scale gas reservoir in the basin [34]. developments of carbonate reservoirs under salt rock in the middle-east of basin and reef flat carbonate reservoirs in the western margin have achieved early success [34], thus reflecting the great potential for the exploitation of the lower Paleozoic carbonate gas reservoir in the Ordos Basin.

Regarding production dynamics, this gas field has experienced four development stages: the early comprehensive evaluation and testing production stage (1991–1996), the pre-production for well exploration stage (1997–1998), the large-scale development stage (1999–2003), and the stable production stage (from 2004 to present). The discovery of a lower Paleozoic gas field stimulated the large-scale development of natural gas in the Ordos Basin, and its successful exploitation has provided enormous support for successful implementation of a west–east major project for gas transmission in China. During the development of the lower Paleozoic gas field, a series of techniques have been proposed to develop large-scale carbonate reservoirs that can guarantee long-term stable gas production for the Jingbian gas field and provide great support for the 5000×10^4 t target in the Changqing oil and gas field. Moreover, stable gas supplementation can decrease the consumption of coal and other unclean resources in large urban areas, thus implicitly protecting the atmospheric environment.

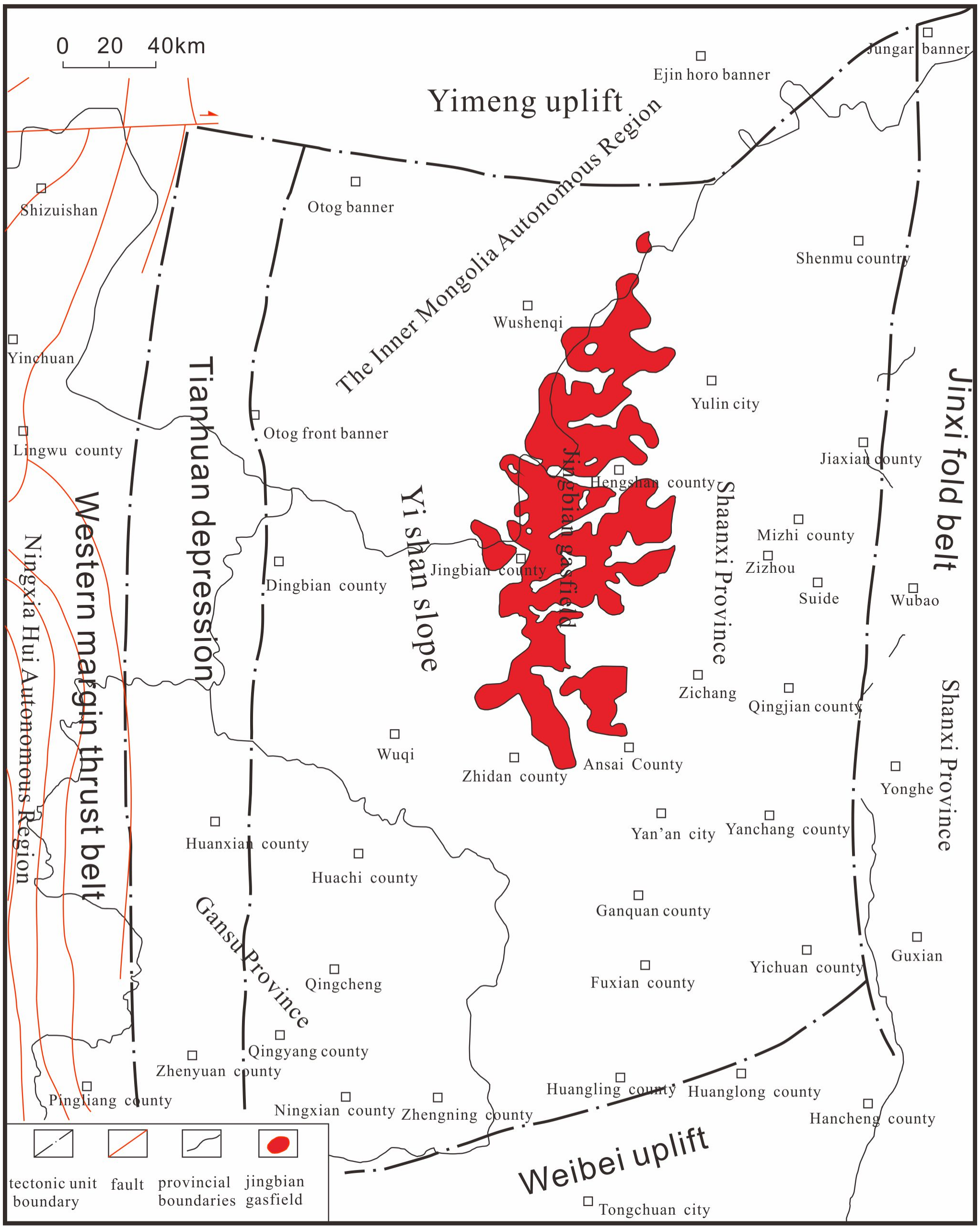

Figure 1. Division of tectonic units and location of the Jingbian gas field in the Ordos Basin.

3. Formation Geological Characteristics

The carbonate gas reservoir in the Ordos Basin, Jingbian gas field, is a weathering crust reservoir. It has unique features influenced by primary deposits, tectonic evolution, paleo-topography, ancient surface runoff, paleo-climatology, and gas source sufficiency. An analysis of carbonate rock composition showed that these rocks are composed of silty dolomite, dolomicrite, grained dolomite, gray dolomite, and cargneule, of which the silty dolomite is the primary mineral. For the formation-water, the main ions in the water are Ca^+ and Cl^-, which are formed in the closed environment.

(1) **Dominated by reservoir sedimentation, crustal uplift and water level lowering, the reservoir has stable horizons, widespread distribution area and multiple gas layers.**

The studied gas reservoir with weathering crust formation in the Ordos Basin is a combined-stratum lithologic subtle trap dominated by paleo-tectonics, lithofacies paleo-geography, and karst paleo-geomorphology. Morphologically deep and slope areas comprise the western Ordos Basin, and the central basin mostly comprises paleo-high tidal flat facies. The depression in the eastern basin is shallow and primarily composed of salt rocks. In this tectonic setting, the northeastern side of the central paleo-uplift is restricted to sea deposits that are composed of carbonates and evaporates. This kind of Paleozoic gas reservoir has stable horizons and large distribution areas that are influenced by a tidal flat environment. As discovered during drilling operations, anhydrite tubercles with dissolved pores are densely distributed in multiple layers, which causes the overlap of vadose and underflow zones. The rhythmical changes of shaliness during the original sedimentation, crustal uplifting, and water level lowering caused overlaps of the above-mentioned zones.

(2) **Controlled by reservoir lithology, karst development degree, direct runoff, and paleo-geomorphology, reservoirs are influenced by grooves of different grades that have caused the formation to have a thin effective thickness, low abundance, and strong heterogeneity.**

Although the distribution area for this kind of reservoir is large (affected by original sedimentation characteristics and lithology difference), its effective thickness is small. Statics analysis has shown that gas reserves per square kilometer are between 0.03×10^8 m^3 and 1.46×10^8 m^3, with an average value of only 0.54×10^8 m^3 in the main area, which means the abundance of gas reserves in the weathering crust gas reservoir is poor.

Weathering crust gas reservoirs have shown strong heterogeneity that is controlled by paleo-geomorphology, direct runoff, and karst development degree. The type and intensity of karstification in different geomorphic units have shown great differences that have led to the vertical partition of karst-rocks and reservoirs. Since the paleo-topography of the western Gaoqiao area is higher than that of the eastern area, the weather denudation is more intense in the west than in the east during Caledonian movement. Karst highlands and karst slopes were developed in karstic paleo-geomorphology from west to east (a karst basin was not developed), and these secondary paleo-geomorphologies can be divided into third-level paleo-geomorphologies. Direct runoff, karst development degree, and weathering crust depth are different in different areas. The Karst highland in the West Gaoqiao area is steeper, so the wells for direct runoff and karst water can reach the stratums beneath member 4 of the Majiagou Formation that penetrates mudstone interlayers. Gypsum rock mainly exists in sub-members 2, 3, and 4 of member 5 of the Majiagou Formation, with karstification in which vertical, deep, and dissolved fractures have intensely developed. Due to the high karst degree and the distribution of effective reservoirs in a paleo-hammock with well-preserved strata, sub-members 1 and 2 of member 5 of the Majiagou Formation are incomplete. Influenced by its relatively small slope angle, the central karst slope area does not have direct runoff. However, direct runoff has wells in grooves that are distributed between karst slope areas. Generally, an abrupt slope favors the rapid infiltration and lateral migration of surface water. The horizon outcropping gypsum rock gradually turns from west to east for the formation of sub-members 2, 3, and 4 of member 5 of the Majiagou Formation. The depth of the vertical leaching grows shallow, which shows that karst water flows slowly lengthwise and that karstification is weak. All of these factors have determined the strong heterogeneity of carbonate reservoirs with weathering crust formation.

(3) **Dynamic behaviors of gas wells show great differences influenced by serious formation heterogeneity.**

The statistical analysis of 677 producing wells in the main area of the Jingbian gas field showed that the cumulative gas production rates and gas reserves have great discrepancies among various gas wells. The average cumulative gas production for these wells is 1.06×10^8 m^3, and the maximum value is 7.6×10^8 m^3 for well G10-14. However, there are 284 producing wells (45% of total wells) for which the cumulative gas production is less than 0.5×10^8 m^3. The average gas reserve controlled by per well is 2.2×10^8 m^3, and the maximum value is 11.4×10^8 m^3 for well Longping1. Nevertheless, there are 298 producing wells (44% of total wells) for which the dominant gas reserve is less than 1×10^8 m^3.

(4) **Influenced by current formation structure, reservoir heterogeneity, paleo-geomorphology, tectonic reversal, and gas source abundance, gas reservoirs generally have no unified bottom and edge water, though they do have remaining interlayer water under sealing conditions, which has caused water-rich zones to be formed in some areas**.

Typically, the weathering crust gas reservoir showed no unified edge or bottom water, though interlayer water is retained in local areas and forms water-rich zones. The Gaoqiao area is located at the convergence of L-form water-rich areas in the Jingbian gas reservoir, which has a complex formation-water distribution pattern. The distribution of gas and water is controlled by regional tectonic setting, gas source abundance, low-amplitude structure, reservoir heterogeneity, and tectonic reversal. Regional tectonic setting is the basic condition that affects formation-water distribution, and insufficient gas sources are the primary reasons for the formation of water-rich zones. Low-amplitude structures and reservoir heterogeneity also play decisive roles in the distribution of local formation-water. The key factor that determines the complex distribution of gas and water is the distribution of ancient grooves and tectonic reversals.

(5) **The production performance of gas wells is seriously impacted by formation-water in some local areas.**

In the zone with retained interlayer water, the proportion of wells that produce water during production testing was shown to be significant. For these wells, gas and water are simultaneously produced, and water production rate variations are large. The water production rate and the probability of water breakthrough for horizontal wells is always larger than those of vertical wells. In the Gaoqiao area, for example, 38 of 150 vertical wells (25.3%) were found to produce water during production testing. The gas production rate was found to be between 0 and 7.97×10^4 m^3/d, with an average value of 1.43×10^4 m^3/d. The water production rate was found to be 0.5~33.5 m^3/d, with an average value of 6.7 m^3/d. In contrast, 10 of 18 total horizontal wells (55.5%) were found to produce water. The gas production rate for these wells was calculated as $0.86\text{~}20.41 \times 10^4$ m^3/d, with an average value of 5.6×10^4 m^3/d. The water production rate was calculated as 8~90 m^3/d, with an average value of 31.0 m^3/d. An illustration of these statistical results is shown in Figure 2. These results can be attributed to the chances of encountering water-rich zones. The probability of drilling into water-rich areas during acid fracturing is low for the vertical wells but high for the horizontal wells. Furthermore, the improvement of reservoir stimulation during production testing has been shown to be able to increase the gas production rate and water production.

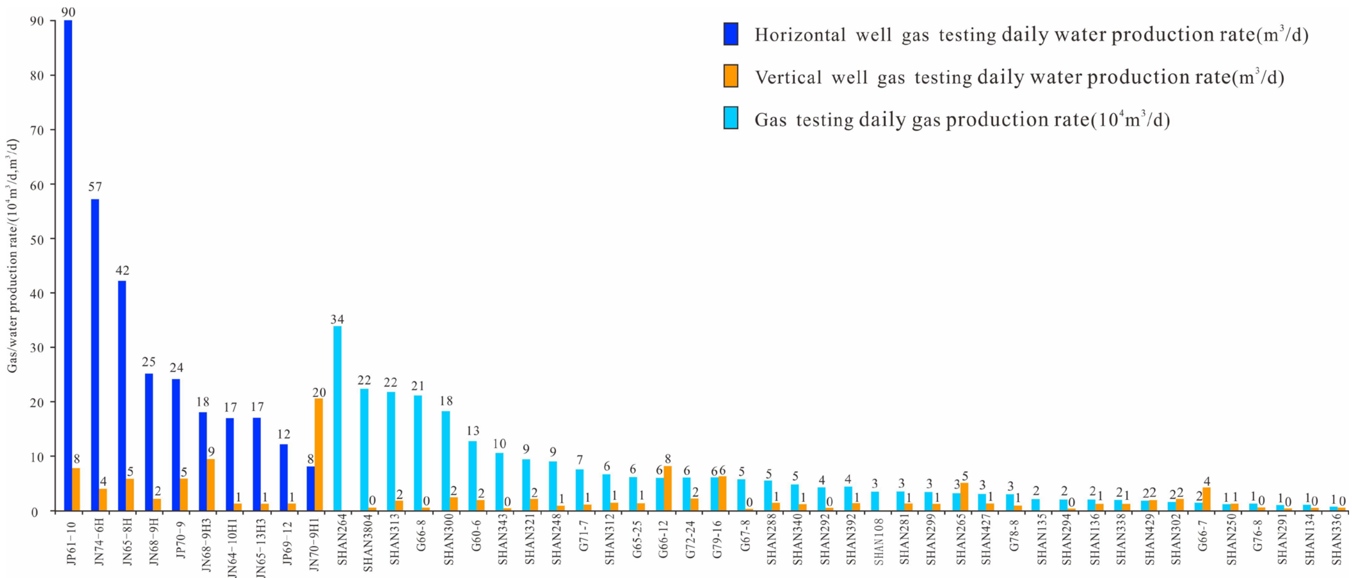

Figure 2. The distribution histogram of gas well testing production in Gaoqiao.

On the other hand, the production wells located in the area with retained interlayer water were found to be significantly influenced by formation-water. The Paleozoic gas reservoir in the Gaoqiao area was chosen as an example for the following reasons:

(1) Well-log interpretation showed that the reservoir is a gas–water formation, as illustrated in Figure 3.
(2) Production testing showed that water production is greater than 2 m3 and the water/gas ratio is larger than 1 m^3/104 m^3.
(3) The producing water–gas ratio is larger than 0.5 m^3/104 m^3.
(4) The content of Cl- is larger than 20,000 mg/L.
(5) The degree of mineralization is larger than 100 g/L.
(6) When the wellhead pressure is equal to 10 MPa, gas production is larger than 1.4 × 104 m^3.

Currently, there are 88 production wells in the Gaoqiao lower Paleozoic gas reservoir with similar characteristics, and 41 of these wells produce water (46.6%). The daily gas production rate for wells that produce water was found to be 0.13×10^4 m^3∼5.29×10^4 m^3, and the daily water production rate was calculated as 0.2 m^3∼18.59 m^3. The average daily gas and water production rate for these wells were shown to be 1.12×10^4 m^3 and 1.53 m^3, respectively, and the water–gas ratio was maintained at 0.19∼14.2 $m^3/10^4$ m^3. It is obvious that the water and gas production rates for water-producing wells vary greatly, which indicates strong formation heterogeneity. Some gas wells, particular for horizontal wells, are seriously influenced by formation-water, which has led to the shut-down of some wells. For instance, Jingnan 57-9H2 comprises sub-members 1 and 2 of member 5 of the Majiagou Formation, and the dilled length ratio for effective formation is 62%. After the utilization of acid fracturing for five stages, gas well productivity was found to be 147.37×10^4 m^3, which demonstrates great production capacity. The gas production rate at the initial stage was calculated as 15∼20 × 10^4 m^3/d and was shown to be influenced by formation-water; after 5 months of production, it rapidly decreased. This well only had been producing for 12 months and is now shut down. The production curve for this well is shown Figure 4.

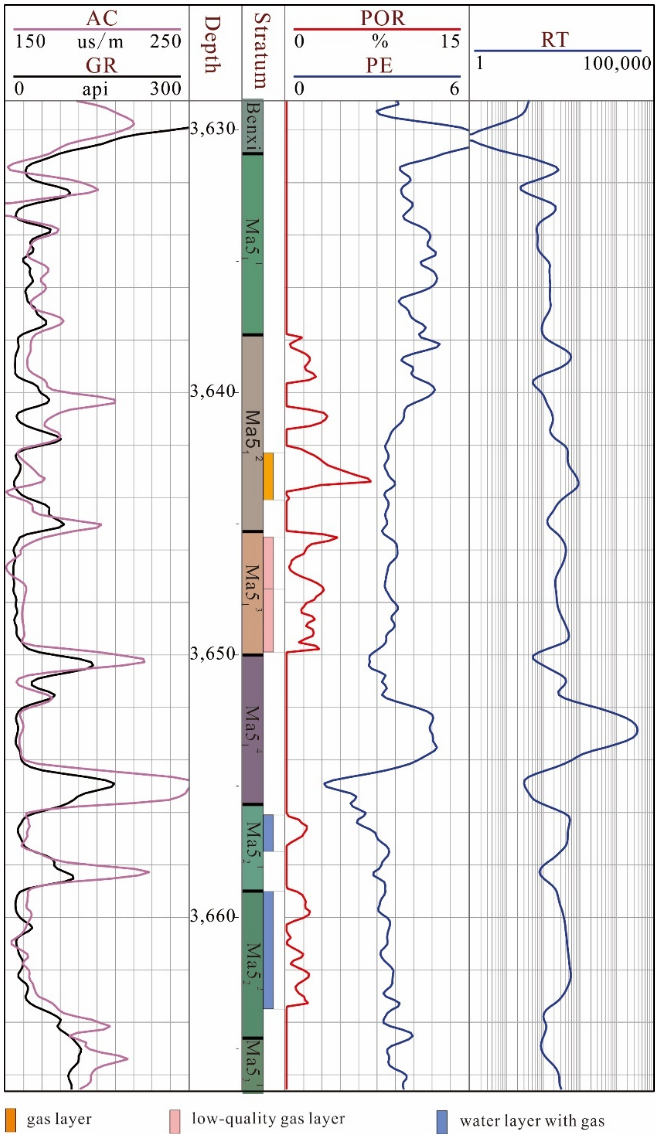

Figure 3. Typical well-log curve and its interpretation results. ($Ma5_1{}^1$, $Ma5_1{}^2$, $Ma5_1{}^3$, and $Ma5_1{}^4$ represents the first, second, third, and fourth layers, respectively, of sub-member 1 of member 5, Majiagou Formation; $Ma5_2{}^1$ and $Ma5_2{}^2$ represent the first and second layers, respectively, of sub-member 2 of member 5, Majiagou Formation).

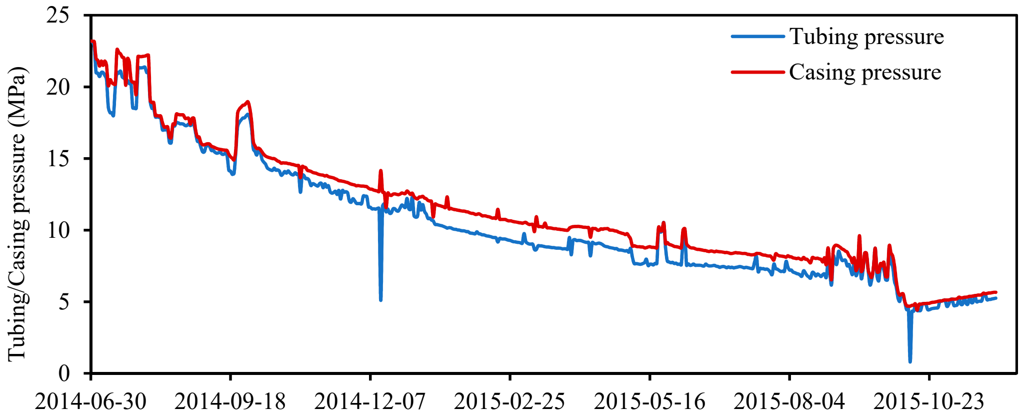

Figure 4. *Cont*.

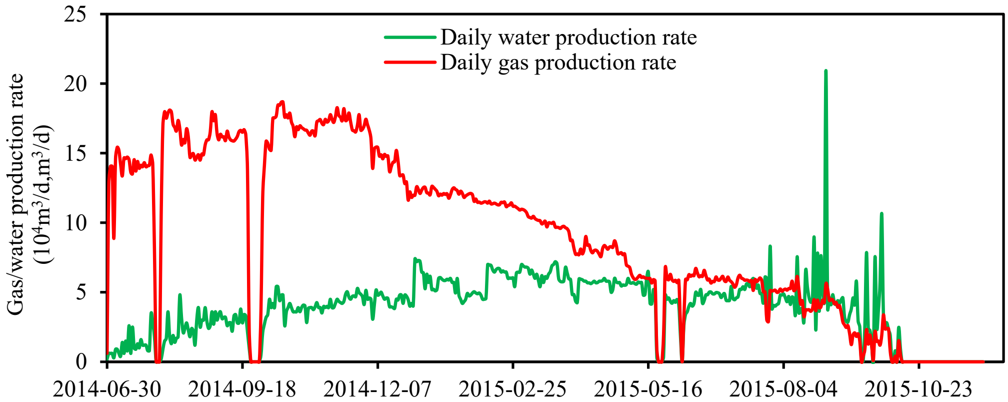

Figure 4. Production curves of well Jingnan 57-9H2.

4. Geology and Production Problems

At present, the development of the lower Paleozoic carbonate gas reservoir requires stable production in the main area and productivity construction in the peripheral area.

Problems for the stable production of the main area include:

(1) As the gas reservoir has entered into the middle or later stage of development, the fine characterization of secondary grooves in the main area is the key to the success of infill wells. Additionally, the basis of long-term stable production for this gas field is reserve distribution.
(2) The prominent contradiction for gas reservoir development is unbalanced exploitation, which has led to the unbalanced distribution of pressure (the pressure in the middle-high and low yield areas is low and high, respectively) and the unbalanced domination of reserves (in the middle-high yield area, the dynamic reserve degree is high, and it is less in the low yield area; in the vertical direction, the dynamic reserve degree for principal producing formation is high, and it is low for other layers). This unbalanced exploitation was found to strongly influence the stable production and regulation ability.
(3) Wellhead pressure is low. We found that the pressure distribution in middle zone and surrounding areas was low and high, respectively. In August 2009, the average reservoir pressure was 11.23 MPa and the wellhead pressure in middle-high production area was 9.37 MPa, which was close to the transport pressure.
(4) Belching wells, low production wells, and water production wells are increasing in number, and the management of gas reservoirs has thus become more difficult.

All these problems have hindered the improvement of gas reservoir recovery and long-term stable gas production in the main area.

The productivity problems of the peripheral area are as follows:

(1) Influenced by sedimentation, diagenism, and paleo-geomorphology, reservoir quality has become worse and the optimization of enrichment areas has become harder.
(2) The reconstruction of paleo-geomorphology in the peripheral area is difficult due to the scarce wells and tiny grooves.
(3) The distribution of formation-water in the western part of weathered crust is complicated.

These problems have increased the complexity of early evaluation and the risk of productivity construction.

5. Optimal Development Techniques and Results

To address the different problems that have emerged in the main and peripheral areas of the low Paleozoic gas reservoir in the Ordos Basin, a series of techniques that can help maintain stable production in the main area and enlarge the scale of productivity construction in the peripheral area have been established.

5.1. Stable Production Techniques and Results in the Main Area

5.1.1. Production Techniques

Five key techniques have been proposed to solve the problems in the main area and aid stable production in the Jingbian gas reservoir: the fine description of grooves with a comprehensive geological modeling technique, a gas reservoir dynamic analysis technique, a pressure-charged mining technique, an optimization technique for horizontal well locations in thin reservoir, and a fine management technique for the gas reservoir.

(1) **Fine description of grooves and comprehensive geological modeling technique.**

Grooves are formation deficiencies that are developed in slope areas with surface runoff and caused by surface water erosion and chemical eluviation. The paleo-grooves for Ordovician weathered crust in the Jingbian gas field were mainly formed by surface runoff erosion and filling, which were controlled by paleo-tectonics, paleo-climate, paleo-hydrodynamic power, and formation lithology. The development of the Jingbian gas field has demonstrated that accurately recognizing the small grooves between wells can significantly influence the success of well drilling. Though restrained by well locations, secondary and tertiary level grooves can be recognized and tracked via the utilization of different groove surfaces in well-logging and seismic analysis—as well as the combination of static and dynamic data—to provide a fine description of the distribution of low Paleozoic grooves.

However, due to the complexity and heterogeneity of erosion grooves, for the geological modeling of weathering crust gas reservoirs, many investigators have proposed the concepts of groove and stratum facies under the consideration of carbonate reservoir peculiarities in the Jingbian gas field, which can be studied with controlled facies modeling [35]. Some researchers have divided the study area into groove facies, reservoir facies, and dry layer facies for geological modeling [36]. The distribution features of grooves should be characterized by facies-controlled modelling techniques, and then a property model can be developed with the aid of well testing, dynamic monition, and gas production data.

(2) **Comprehensive gas reservoir dynamic analysis technique.**

In terms of the unbalanced exploitation of gas reservoirs, the formation pressure in the main area and dynamic reserves can be evaluated with pressure, well, and production testing data, and then comprehensive gas reservoir dynamic analysis technique can be used. Due to different percolation characteristics and dynamic features for gas wells, there are few formation pressure testing data and an unstable schedule for gas wells; accordingly, multi-method evaluation techniques based on pressure-drop and production rate transient analyses have been proposed for the estimation of gas reserves for low-permeability and heterogeneous reservoirs. These techniques can provide support for the evaluation of single-well dynamic reserves and their varied features in the Jingbian gas field. On the other hand, because formation permeability is low and the recovery of wellhead pressure after shutting down wells is slow, some pressure evaluation methods—such as corrections for wellhead pressure and the extension of deliverability equations—have been proposed to provide support for the fine evaluation of change laws and distribution features in gas field formation pressure. A diagram illustrating these methods is shown in Figure 5.

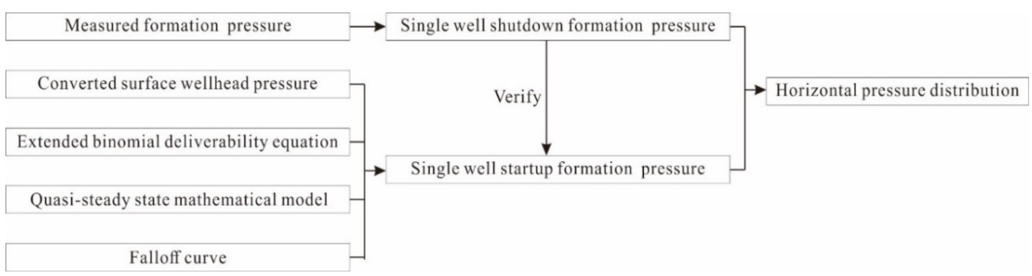

Figure 5. The evaluation technology for formation pressure measurements of shut-in gas wells.

(3) **Pressure-charged production technique.**

Following decades of development in the main area of the Jingbian gas field, the gas well pressure is continually decreasing. However, pressure-charged production can be used to improve gas reservoir recovery in the main area for long-term stable production. The surface pressure system in the main area of the Jingbian gas field was found to be 6.4 MPa. The abandonment pressure was found to be 9.7 MPa, with a depleted gas production rate of 1000 m^3/d. However, the abandonment pressure could be reduced to 6.1 MPa in the Jingbian gas field using the pressure-charged production technique, which has enormous potential due to the reservoir's large scale. However, the large area, many wells, and seriously unbalanced development also mean that the single-well pressure-charged technique has limitations. Table 1 compares the pros and cons of different pressure-charged techniques (Table 1).

Table 1. Comparison of different pressure-charged methods.

Pressurization Method	Advantages	Disadvantage	Prediction Gas Recovery after 30 Years (%) (Wellhead Pressure 2 MPa)	Total Investment (One Hundred Million Yuan)
Single-well pressurization	No need for pipe network reconstruction and the consideration of unbalanced gas field exploitation	Too many pressurized points, heavy workload, maintenance difficulty, and poor development benefits	56.3	23.7
Gas gathering station pressurization	Small workload and easy management	Too many stations, difficulties in compressor choice and management	56.2	15.3
Regional pressurization	Efficient reduction in station numbers and lowering of difficulties in production and management	Hard to divide compress cells due to pressure drawdown desynchrony between wells	56.4	17.6
Concentrated pressurization	Least required stations and little maintenance work	High pipe network reconstruction costs and high operation risks	56.3	25.1

The results show that the gas field development effects of different pressure-charged techniques are almost identical, and the selection of optimal pressure-charged techniques depends on economic and engineering factors [37].

(4) **Optimization technique for horizontal well locations in thin reservoir.**

Sub-members 1 and 2 of member 5 of the Ordovician Majiagou Formation in the Jingbian gas field comprise a trap that combines paleo-geomorphology and lithology and that has low porosity, low permeability, thin layers, and strong heterogeneity. The gas production rate and dynamic well gas reserves for conventional vertical wells are low, and there is significant unbalanced development. Fully developing geological reserves and improving single-well production and gas recovery are the keys to the long-term stable gas field production. For horizontal wells in weathering crust reservoirs that are full of erosion grooves and have thin primary formation, low-amplitude structure variation, and strong reservoir heterogeneity, optimization can be accomplished presented through the utilization of 3D seismic technology, geological formation evaluation, techno-economic analysis, and gas reservoir numerical simulation [38]. Firstly, an analysis of the relationship between formation permeability and the net present value (NPV) conducted with a comprehensive technical and economic evaluation method showed that the area that could be exploited with horizontal wells can be determined when permeability is larger than $0.1 \times 10^{-3} \mu m^3$. Secondly, according the distribution law of abundant natural gas resources and karst paleo-geomorphology analysis, geomorphic units of karst monadnock and gentle slope were chosen as the areas that can be exploited within horizontal wells. Finally, five principles for deployment with horizontal wells were determined as follows:

1. The results of reservoir evaluation demonstrated that the residual thickness of sub-members 1 and 2 of member 5 of the Majiagou Formation is larger than 20 m and that the horizontal distribution of formation is steady.
2. The thickness of sub-member 1 of member 5 of the Majiagou gas-bearing formation is greater than 2 m.
3. Reservoir physical properties is strong, and the formation is of class I or II.
4. The formation structure is relatively flat.
5. Production testing for adjacent vertical wells demonstrated that gas production is stable. The vertical distance between horizontal wells meets the requirement for production without interference.

(5) **Fine gas reservoir management.**

In recent years, development techniques and management system for the Jingbian gas field have been continually optimized, which has led to the development of a suitable management pattern. To propose a novel gas management pattern, which can be used to improve the accuracy of flowing unit evaluation and determine the necessary steps for gas reservoir developments, the authors considered the flowing element as the management object and conducted experiments that considered a combination of geology, engineering, and operator factors. According to the gas–water distribution, production dynamics, reservoir properties, monitored fluids properties, current formation pressure, and other static parameters, criteria for flowing unit classification were established. Additionally, various technical strategies for the stable production and enhancement of gas recovery were formulated for each unit. Table 2 shows the three primary classes.

Table 2. Classification criteria and results for developed units in Jingbian gas field.

Types	Class I	Class II	Class III
Dynamic reserve ratio/%	>30.0	15∼30	Located in water-rich area
Average absolute open-flowing gas rate/(10^4 m^3/d)	>20.0	<20	
Average cumulative gas production for unit pressure drop (10^4 m^3/MPa)	>900	<900	
Recovery factor/%	>10	<10	
Average allocating gas production rate/(10^4 m^3/d)	>3.0	2.0∼3.0	
Water–gas ratio (m^3/10^4 m^3)	<0.18	<0.20	>0.60
Division results	13	17	6

Class I: This kind of flowing unit is characterized by four large factors and one low factor that refer to a large ratio between dynamic and static reserves, a high recovery extent, a high gas well productivity, a large cumulative gas production rate with a unit pressure-drop, and a low gas well pressure, respectively. This kind of unit is primarily located in the main area of the gas field and should be addressed with the technical strategies of fine characterization, deep potential exploitation, and enhanced gas recovery. For areas that are not dominated by this well pattern, infill wells should be drilled to improve the area-dominated extent of gas reserves. The dominated degree in the vertical direction for this gas field can be improved by perforating the new gas-bearing layer and side-tracking.

Class II: This kind of flowing unit can be characterized by four low factors and one large factor: a low ratio between dynamic and static reserves, a low recovery factor, a low gas productivity, a low cumulative gas production rate with a unit pressure-drop, and a high formation pressure. This kind of unit is primarily located in the eastern part of the gas field and should be addressed with the technical strategies of block optimization, scale enlargement, and improvements in single-well gas production rate. Horizontal wells are preferable for use during development to improve individual well producing rates.

Class III: This kind of unit can be characterized by two large factors and one low factor: a high water production rate, a high water–gas ratio, and a low formation pressure. Influenced by water production, this kind of unit should be addressed with the technical strategies of evaluation enhancement, internal water drainage, and external water control; of these, drainage is the primary measure that can improve gas recovery. A pattern in which the flowing unit is the management object can improve the efficiency of gas management, which also can allow for fine gas reservoir evaluation.

5.1.2. Development Strategies with the Presented Techniques

The development plan and results of the use of the presented techniques in the main area are as follows:

(1) Ten first-order grooves, seventy-two second-order grooves, three hundred and eighty-two third-order grooves, and some fourth-order grooves were characterized. Fine descriptions for different ranks of grooves have allowed for a more accurate characterization of low Paleozoic reservoir architecture, which has provided a good foundation for comprehensive reservoir geological research. Following four steps regarding facies-control, formation, physical properties, and gas content, a 3D geological model for the main area of gas reservoir could be developed. The new geological model could be used to recalculate the main area reserves in combination with production data to form the basis of stable production and gas recovery improvements for the main area.

(2) The ratio between static and dynamic reserves was found to be 34.06% in the main area and 19.89% in the east of Qiantai, which indicates that the exploited gas reservoir extent is low for the whole reservoir and has great potential for gas recovery enhancement. According to the evaluated pressure distribution and fine gas reservoir description, the north Beier district, the Shan66 district, the Shan175 district, the south Naner district, and the Shan106 district are the best places for new well drilling, which can enhance the produced gas reserve degree in the main area.

(3) Based on production dynamics and surface construction in gas field, the regional pressure-charged and gas collection pressure-charged techniques were determined to be main and auxiliary ways to enhance gas recovery. The principle of integrated planning and implementing by steps has also been employed, and the gas reservoir has been divided into thirty elements that can support the arrangement of the pressure-charged project. The pressure-charged experiments showed that the stable production period can be prolonged for 2–3 years, and the recovery degree of the gas reserves can be increased by 14.6% in the Jingbian gas field.

(4) The gas well production rate can be greatly increased with the horizontal well development technique in thin gas formation, and development benefits also can be improved. In 2011, nine horizontal wells with an average length of 1145 m were drilled. The average absolute gas flow rate for five wells was found to be $10^8 \times 10^4$ m^3/d, which was nine times that of surrounding vertical wells. Horizontal length for the well Jingbian 012-6 was found to be 1161 m, and the drilled effective reservoir thickness was found to be 1048 m, which accounted for 90.3% of total drilled formation length. After acid fracturing for seven segments, the absolute gas flow rate was found to be 219.27×10^4 m^3/d.

(5) The main area in the Jingbian gas field can be divided into 36 units, and the well-spacing density, recovery factor, and remaining gas reserves can be calculated for each unit to provide the basis for the adoption of development strategies in different flowing units.

5.2. Techniques for Improvement of Production Scale in Peripheral Area

Enrichment area optimization, paleo-geomorphic restoration, and formation-water distribution evaluation techniques have been established to solve problems and strongly support productivity construction in the peripheral area.

5.2.1. Production Techniques

(1) **Optimization technique for enrichment area.**

Each method for the evaluation of reservoir properties has disadvantages in carbonate reservoirs with strong heterogeneity. Therefore, during the optimization process for enrichment areas in the peripheral zones of the Jingbian gas field, a method that combines multiple factors was applied to screen for some quantitative and qualitative factors including micro-facies, reservoir/gas-bearing formation thickness, residual thickness for weathered crust, porosity, permeability, gas saturation, and shale content distribution. Then, a weight index was normalized and evaluated, and the weighted average process was conducted. Finally, reservoir properties could be comprehensively evaluated and the reserve for each layer could be determined. After the superposition and selection of these enrichment layers, the areas that are suitable for development could be determined.

(2) **Paleo-geomorphic restoration technique.**

Conventional paleo-geomorphic restoration techniques include the sedimentology restoration, impression, residual thickness, layer flattening, and high-resolution paleo-geomorphic sequential stratigraphy restoration methods. Each of these methods needs well drilling, well-logging, core, slice, and seismic data. Considering each method's advantages and disadvantages, the dual-interface paleo-geomorphic restoration method has been established as the most suitable method for the evaluation stage of gas reservoirs.

This method is based on two interfaces, namely a typical horizon for overlying strata and a basic horizon for underlying strata. The typical horizon for overlying strata is similar to the top reference surface in the impression method and the top flattening surface in the layer flattening method. The selection of the typical horizon for overlying strata is based on high-resolution sequence stratigraphy theory. The overlying isochronal stratigraphic framework was developed through the utilization of corrections for the high-resolution base level cycle. The transfer surface (sequence boundary or maximum flooding surface) of the base level cycle was chosen as overlying marker zone while considering sedimentary analysis results. The overlying marker surface is a horizon that lies on the flattened formation. This marker surface is the transfer surface in the base level cycle that can be easily correlated between wells and has good isochroneity. The formation's bottom morphology beneath the marker surface can reflect the original paleo-geomorphology features before formation deposition and after flat marker surface deposition. The basic underlying stratum is the starting horizon for the calculation of easily selected paleo-geomorphology values. The first well-developed formation under a weathering crust's unconformable surface should be determined first. Then, the maximum thickness (H_3, constant) from the overlying marker surface to the formation's bottom can be calculated. The underlying marker surface is a horizon that is lower than overlying marker surface for the value of H_3 (Figure 6). The paleo-geomorphology value of a drilled well should be defined after the recognition of two interfaces and a contour map for paleo-geomorphology, which should be drawn according to seismic data. Finally, a paleo-geomorphic unit can be divided by regional paleo-geomorphology features.

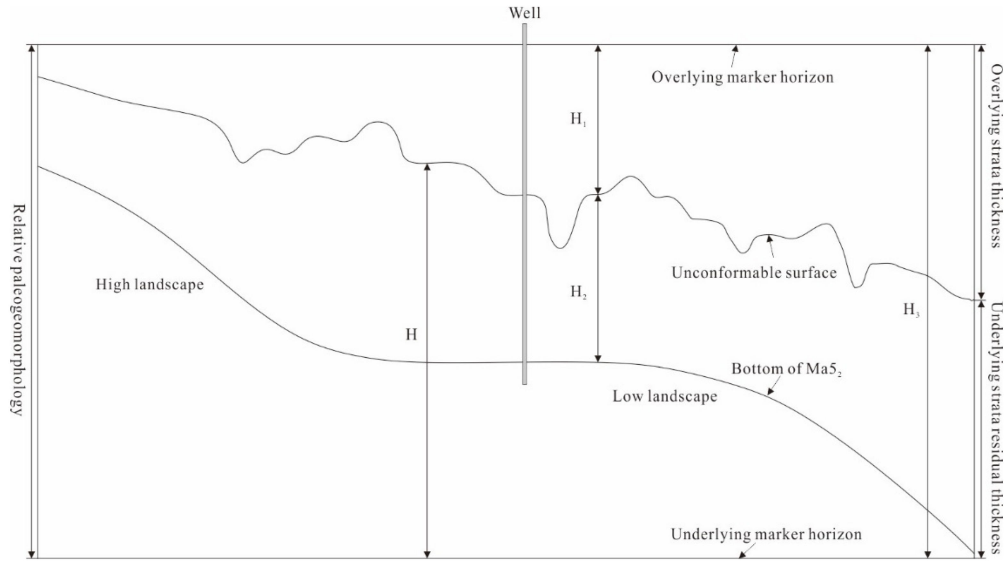

Figure 6. Geomorphology division principle for dual-interface method.

(3) **Evaluation technique for formation-water distribution.**

The distribution of formation-water in the peripheral area of the Jingbian gas field is complicated. It has been difficult to find an effective way to avoid drilling formation-water during development. To solve this problem, we comprehensively utilized stationary and dynamic methods to characterize the distribution of gas and water; after identifying various types, a classification standard could be established for permeable formation bodies (Table 3). This standard subdivided the permeable reservoir bodies into six types: high-permeability formation without water, high-permeability formation with condensed water, high-permeability formation with sealed water, low-permeability formation with sealed water, low-permeability formation with condensed water, and low-permeability formation without water. The distribution of different types of permeable formation bodies was characterized with a combination of comprehensive evaluation results regarding the gas reservoir (Figure 7). Consequently, optimal well locations were determined according to the following order: high-permeability formations without water, low-permeability formations without water, high-permeability formations with condensed water, and low-permeability formations with condensed water.

Table 3. The dynamic and static classification standard of permeable formation bodies.

Permeable Formation Body Types	Static Criterion		Dynamic Criterion	
	Permeability (mD)	Saturability (%)	Gas Output (10^4 m^3/d)	Gas–Water Ratio (m^3/10^4 m^3)
High-permeability formation without water	≥0.6	≥75	≥1.2	≤0.2
High-permeability formation with condensed water		≥45–75		0.2–0.6
High-permeability formation with sealed water		<45		>0.6
Low-permeability formation with sealed water	<0.6	<50	<1.2	>0.6
Low-permeability formation with condensed water		≥50–80		0.2–0.6
Low-permeability formation without water		≥80%		≤0.2

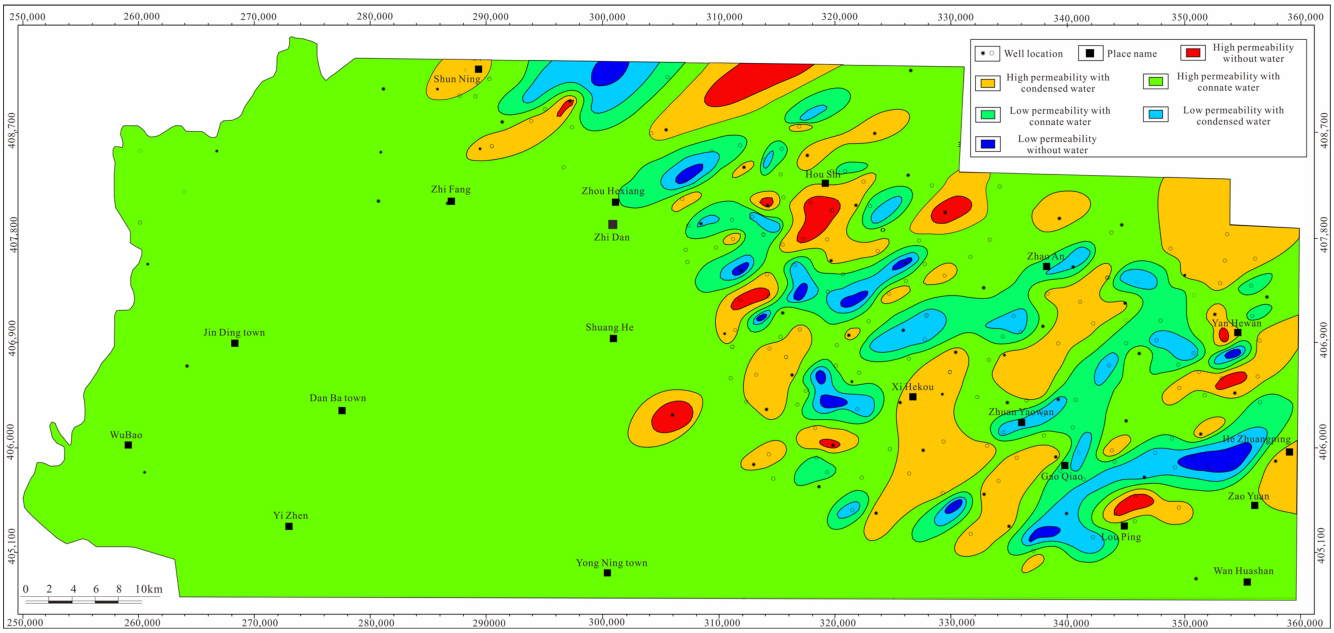

Figure 7. Distribution map of permeable formation bodies in Gaoqiao area, Ordos Basin.

The comprehensive evaluation of formation-water distribution with stationary and dynamic methods can guide the development of wells in areas rich in retained interlayer water in the peripheral area of the Jingbian gas field.

5.2.2. Development Strategies with the Presented Techniques

Through the utilization of the three presented production techniques for the peripheral area, the development plan for this area is as follows:

(1) With the optimization technique, the gas reserve for the enrichment area of the Shenmue gas field was found to be 44.2 billion cubic meters; this information can be used to guide the optimization of well placement and production facility construction.

(2) The paleo-geomorphology of the top Ordovician karst weathering crust in the Gaoqiao area was assessed using the dual-interface paleo-geomorphic restoration method. The first order paleo-geomorphic unit of weathering crust in the Gaoqiao area can be subdivided into two kinds of second order paleo-geomorphic units, namely karst highland and karst slope. Meanwhile, there are seven kinds of third order paleo-geomorphic unit, namely flat, platform, depression, monadnock, main monadnock, groove, and main groove. This classification scheme can guide the setting of well patterns in the Gaoqiao area.

(3) According to the evaluation results regarding the distribution of formation-water in the Gaoqiao area and data of the 21 horizontal wells in the lower Paleozoic, seven wells that can normally produce are located in an area with a low risk of water breakthrough and all other wells save one cannot produce normally and are located in zones with a high risk of water breakthrough (sealed aquifer).

Through the utilization of the presented optimal production techniques for the main and peripheral areas in the Ordos Basin, it is predicted that gas production can be maintained at 5.5 billion m^3 per year and be stable before 2025. It should be noted that the presented techniques have been conducted in practice. The techniques have been additionally used in geological exploration, gas reservoir development, and well operation, which has made it difficult to compare the results of different methods across the entire development process. Different comparative methods can be used to select optimal techniques. Therefore, a scheme that integrates all techniques will be optimal and lead to the most benefits.

6. Conclusions

The lower Paleozoic carbonate gas reservoir in the Ordos Basin is a typical karst weathering crust carbonate gas reservoir that has a large distribution area, low abundance, strong heterogeneity, and multiple gas layers. Currently, this reservoir faces many problems, including the complexity of groove distribution, a low degree of gas reservoir recovery, an unbalanced exploitation degree, and a low wellhead pressure. In addition, some local regions are rich in water, which significantly influences the production of gas wells.

To deal with the emerging problems of this carbonate gas reservoir, five key techniques have been presented to maintain stable gas production in the main area: (1) the fine description of grooves and comprehensive geological modeling, (2) the comprehensive dynamic analysis of the gas reservoir, (3) pressurized development, (4) the optimization of horizontal well locations in the thin reservoir, and (5) the fine management of the gas reservoir. For the peripheral area, which has faced worse reservoir quality, complicated formation-water distribution, and unclear paleo-geomorphological distribution, three key techniques have been developed: (1) the optimization of the enrichment area, (2) dual-interface paleo-geomorphic restoration, and (3) the evaluation of formation-water distribution, with the division of permeable formation bodies conducted via stationary and dynamic methods.

With the presented techniques, the gas production of the main area can be maintained at 5.5 billion cubic meters per year and be stable before 2025. The predicted natural gas reserve of the peripheral area was found to comprise 1 trillion cubic meters in the preliminary evaluation, and the potential gas production rate for this area could reach a value of 4.5 billion cubic meters per year, which would greatly contribute to the goal of one billion cubic meters of gas production per year for the lower Paleozoic carbonate gas reservoir in the Ordos Basin. Furthermore, considering the middle and lower gas layers in the east basin and the potential carbonate gas-bearing formations in the west basin. The Lower Paleozoic carbonate gas reservoir in the Ordos Basin has good prospects for exploration and development.

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