RESEARCH ARTICLE

Professional Evaluation and Distribution Patterns of Shale Gas Reservoirs in the Wufeng Formation-Long 11 Sub-member of Well Block Z205, Sichuan Basin

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Abstract

The deep shale gas ($\geq$ 3500 m) in the Z205 well area is a critical exploration and development target in the Sichuan Basin. The shale gas reservoirs of the Upper Ordovician Wufeng Formation – Lower Silurian Longmaxi Formation (Long 1_1 submember) in this area are characterized by deep burial and significant vertical and lateral heterogeneity. The Long 1_1 submember is subdivided into the Wufeng Formation, Long 1_1^1, Long 1_1^2, Long 1_1^3, and Long 1_1^4. This study conducts a detailed stratigraphic comparison based on integrated logging, core analysis, and analytical test data from the well area, clarifying the longitudinal and lateral distribution patterns of the reservoirs. Utilizing the TOPSIS algorithm, a reservoir classification and evaluation model integrating subjective weights and objective analysis is established. Reservoirs are classified as Class I when $C_i \geq 0.6$, Class II when $0.4 \leq C_i < 0.6$, Class III when $0.2 \leq C_i < 0.4$, and non-reservoir when $C_i < 0.2$. Results indicate significant directional variations in the thickness of each sub-layer within the Wufeng-Long 1_1 submember. The main reservoir intervals, Long 1_1^1 to Long 1_1^3, exhibit an overall thickening trend from north to south and west to east. At least three stable, laterally extensive Class I continuous reservoir units are identified vertically. The No. 1 Class I reservoir is primarily distributed from Long 1_1^1 to Long 1_1^3 and the basal part of Long 1_1^4, being most developed in the central synclinal areas (Huliongchang, Gaoshikuan, and northern Panlongchang Synclines). The No. 2 and No. 3 Class I reservoirs are mainly located within the middle-upper sections of Long 1_1^4. They are most developed within the Gaoshikuan Syncline, thinning towards the southern and northern margins. The research outcomes provide significant guidance and reference value for the subsequent exploration, development, and related research of shale gas in the Z205 well area and analogous regions.

Keywords: Sichuan basin, z205 well area, deep shale gas, TOPSIS algorithm, reservoir classification evaluation, reservoir distribution pattern.

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1 Introduction

Shale gas is a kind of unconventional low-carbon energy that is stored in the form of adsorbed gas and free gas within mudstone. It is characterized by self-generation and self-storage [1–5], and is mainly distributed in the United States, China, Argentina and South Africa. China is rich in shale gas resources. Marine, terrestrial and marine-terrestrial transitional shale rich in organic matter are widely distributed. They have characteristics such as multi-layer distribution, multiple formation types, and complex post-event modification. The geological features and enrichment patterns of shale gas in China have many specialities [6, 7]. The deep shale gas in the Upper Ordovician Wufeng Formation - Lower Silurian Longmaxi Formation section in the Sichuan Basin is the main area driving the growth of China's shale gas production. Currently, shale gas has been developed on a large scale and commercially in the reservoirs with a burial depth of less than 3500m. According to the China Petroleum Shale Gas Development Plan, the production share of deep shale gas (with reservoir burial depth ranging from 3500 to 4500m) will increase from 2% to 47%. Deep shale gas has become the focus of current exploration and development [8–11].

The Zigong block is a newly explored area for shale gas production capacity assessment by China National Petroleum Corporation in the recent period [12]. The Z205 well area is located within the Ziliujing Structure of the Zigong block. The Wufeng Formation - Long 1_1 submember in the well area has the characteristics of deep burial (burial depth $\geq$ 3500m), large reservoir thickness, and superior reservoir quality. It is one of the main blocks for shale gas exploration and development in the Southwest Oil and Gas Field.Compared with the shallow and middle-layer shale gas, the geological conditions of the deep-layer shale gas in the Z205 well area are more complex. The production of a single well shows characteristics such as high initial production, rapid decline in gas production and pressure, and low ultimate recoverable reserves. At the same time, the identification of geological sweet spots is difficult, and realizing large-scale industrialization poses significant challenges [13, 14].

This article is based on the logging, core analysis, and laboratory testing data from the Z205 well area. It conducts a detailed comparison of the strata of the Wufeng Formation - Long 1_1 submember in the well area, and clarifies the longitudinal and lateral distribution characteristics of the reservoirs in the well area. Optimize the TOPSIS algorithm, and based on the previous experience in shale gas reservoir evaluation, combined with subjective weights and objective analysis, a classification evaluation model for shale gas reservoirs in the Wufeng Formation - Long 1_1 submember of the Z205 well area was established.

The model indicates that in the Z205 well area, there are three sets of stable, planarly distributed Class I continuous reservoirs vertically, with great resource potential. This provides guidance and reference for the subsequent exploration and development of the well area as well as the research work on shale gas at home and abroad.

2 Regional Geological Background

The Z205 well area is located within the Ziliujing Structure. The structure as a whole is oriented in a north-east direction. From west to east, it mainly features the Huangjiachang, Longshizhen, Shengdianshan, Yunzhongchang and other structures. The well area is mainly composed of the Xindian, Huilongchang, Gaoshikang and Panlongchang synclines, with a simple shape and gentle strata. The structures within the Z205 well area are oriented in a north-easterly direction and are distributed in a strip-like pattern. The Huangjiachang structure in the north, the Longchang Longshizhen structure in the east, and the Shengdianshan structure are relatively steep, while the structures in the southwest are relatively gentle, mainly consisting of anticlines and the terminal parts of the structures(Figure 1).

The 3D seismic data shows that the burial depth of the Longmaxi Formation in the area varies significantly, ranging from 3200 to 4200m. The burial depth at the anticline is greater than 3500m, while the burial depth at the core of the anticline is larger, and it gradually becomes shallower towards the back of the syncline. The preliminary exploration and evaluation results indicate that the shale gas resources of the Longmaxi Formation are greater at the syncline than at the anticline. However, the burial depth at the syncline is very large, which poses significant challenges for drilling operations and subsequent fracturing procedures.

3 The Stratigraphic Distribution Characteristics of the Wufeng Formation - Long 1_1 Submember

Based on electrical and lithological characteristics, the Long 1_1 submember of the well area is divided into

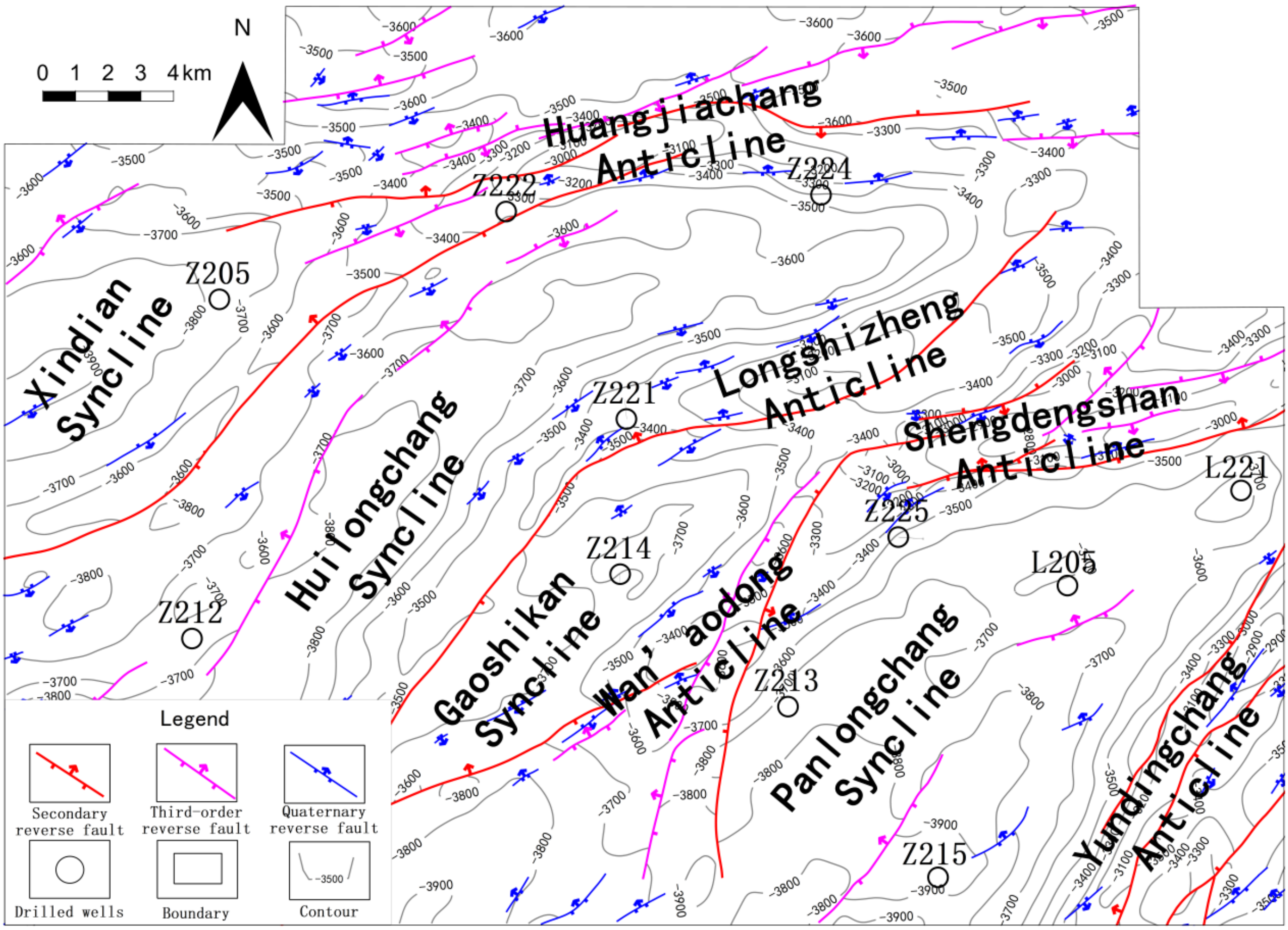


Figure 1. The seismic reflection structure map of the bottom boundary of the Wufeng Formation of the Upper Ordovician in the Z205 well area.

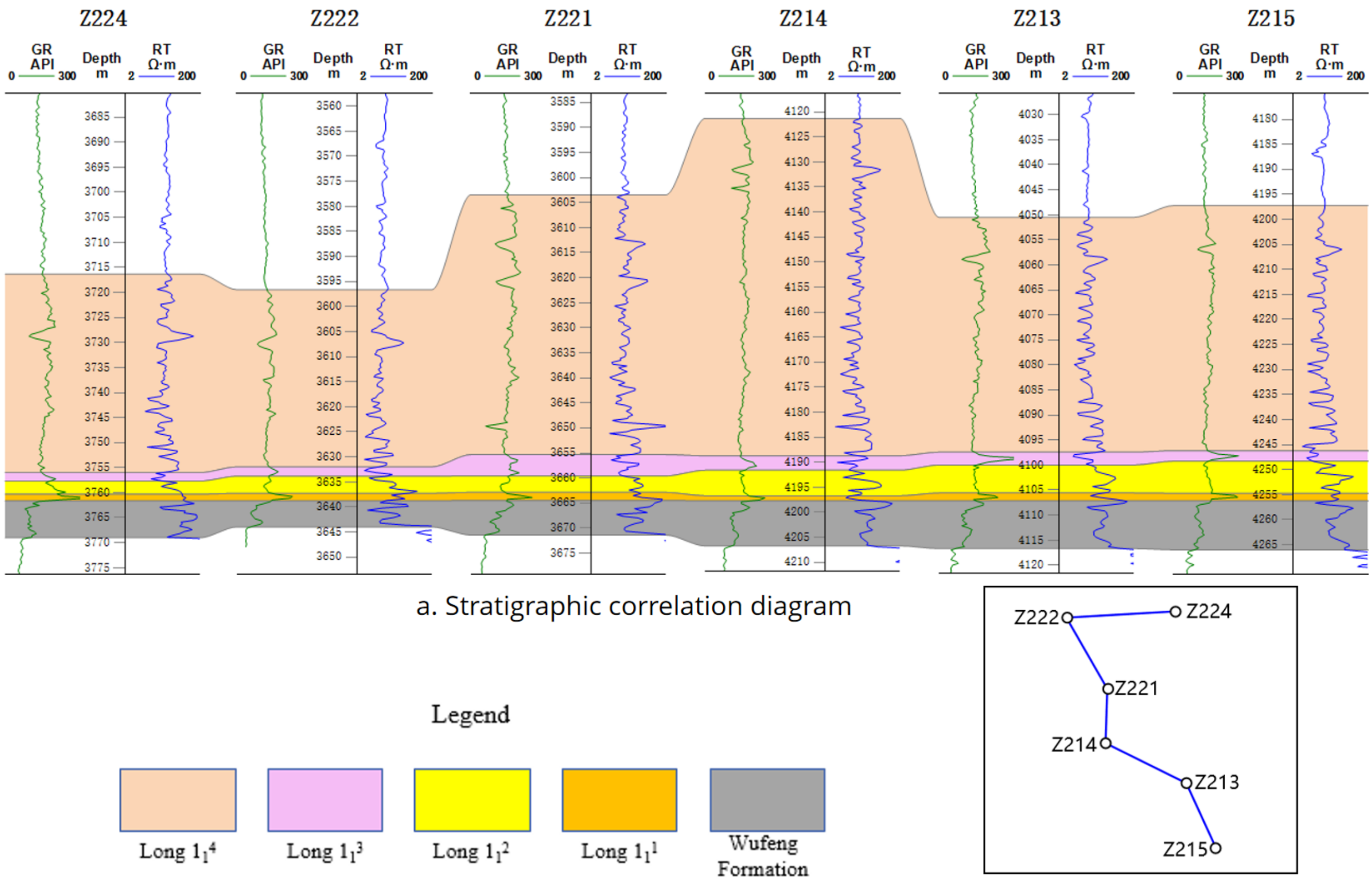
four sublayers: Long 1_1^1, Long 1_1^2, Long 1_1^3, Long 1_1^4. The preliminary research results indicate that the organic-rich black shale layers of Long 1_1^1 - Long 1_1^3 in the lower part of the Wufeng Formation - Long 1_1 submember are the main productive layers in the study area.

The well area drilling results (Figures 2 and 3) show that the thickness of the Wufeng Formation ranges from 4.1 to 10.7m. The thickness gradually increases from north to south, and remains relatively stable in the east-west direction. The Long 1_1^1 to Long 1_1^3 in the well area are the main gas-producing layers of shale gas. The thickness of the Long 1_1^1 ranges from 1.0 to 3.1m, and it is stable in the north-south direction. The thickness on the east and west sides of the well area is greater than that in the central part of the well area. The thickness of the Long 1_1^2 ranges from 2.6 to 6.4m, and it gradually increases from north to south. The thickness of the Long 1_1^3 ranges from 1.6 to 5.0m. It gradually thins out from the central part of the building towards the periphery. The Long 1_1^4 has the thickest sedimentary thickness within the Wufeng Formation - Long 1_1 submember, ranging from 29.1 to 69.4m. It gradually thickens from west to east and gradually thins on the north and south sides. The total thickness of the Long 1_1^1 - Long 1_1^3 is 5.6 to 10.0m. As a whole, it shows a gradually increasing trend from north to south and from west to east. Overall analysis shows that there are significant differences in the spatial variations of the thickness of each individual layer of the Wufeng Formation - Long 1_1 submember in the Z205 well area.

4 Reservoir Characteristics and Distribution Patterns

4.1 Comprehensive Evaluation of Reservoir Characteristics

The test results from the Wufeng Formation - Long 1_1 Submember in the Z205 well area (Table 1) shows that the reservoir quality of the Long 1_1 submember in the well area is generally better than that of the Wufeng Formation. The reservoir quality of the Long 1_1^1 - Long



b. Section position map

Figure 2. The north-south stratigraphic comparison map of the Wufeng Formation - Long 11 submember in the Z205 well area.

1_1^3 is better than that of the Long 1_1^4. The reservoir qualities of the Long 1_1^1 - Long 1_1^3 are basically the same with each other. The Long 1_1 submember as a whole exhibits the characteristic that the reservoir parameters become better as one goes deeper.

The highest-quality reservoirs of the Wufeng Formation - Long 1_1 submember in the well area are mainly distributed in the Long 1_1^1 - Long 1_1^3. The total organic carbon (TOC) content of this section of the strata ranges from 3.2% to 7.3%, with an average of 4.5%. The porosity range is 3.5% to 6.9%, with an average of 5.2%. The range of gas content is 3.9% to 11.0%, with an average of 7.6%. The range of brittle minerals is 53.9% to 83.6%, with an average of 71.8%. The static conditions of the reservoir are excellent.

At the same time, the Young's modulus of the Long 1_1^1 - Long 1_1^3 is 31.5GPa to 45.3GPa, with an average of 39.1GPa. Poisson's ratio ranges from 0.192 to 0.240, with an average of 0.211. The horizontal stress difference ranges from 12.2MPa to 13.9MPa, with an average of 13.2MPa. This section has a relatively high Young's modulus, a low Poisson's ratio, and a low horizontal stress difference, indicating that the compressibility is also good.

4.2 Reservoir Quality Classification

At present, the mainstream evaluation method in the Sichuan Basin is to conduct semi-quantitative evaluation of the reservoir based on the TOC content, porosity, gas content (the sum of free gas and adsorbed gas), and the content of brittle minerals. The TOC content not only affects the intensity of hydrocarbon generation, but also influences the development of organic matter pores and the content of adsorbed gas. The porosity of shale is an important parameter for characterizing the storage performance and quality of shale gas reservoirs. The gas content of shale gas is the sum of the free gas and adsorbed gas in the shale gas reservoir. The gas content of the shale gas reservoir is an indication of the enrichment of shale gas, and it is also an important parameter that determines whether shale gas has economic exploitation value. The content of brittle minerals is mainly used for evaluating the compressibility of the reservoir. A high content of brittle minerals is

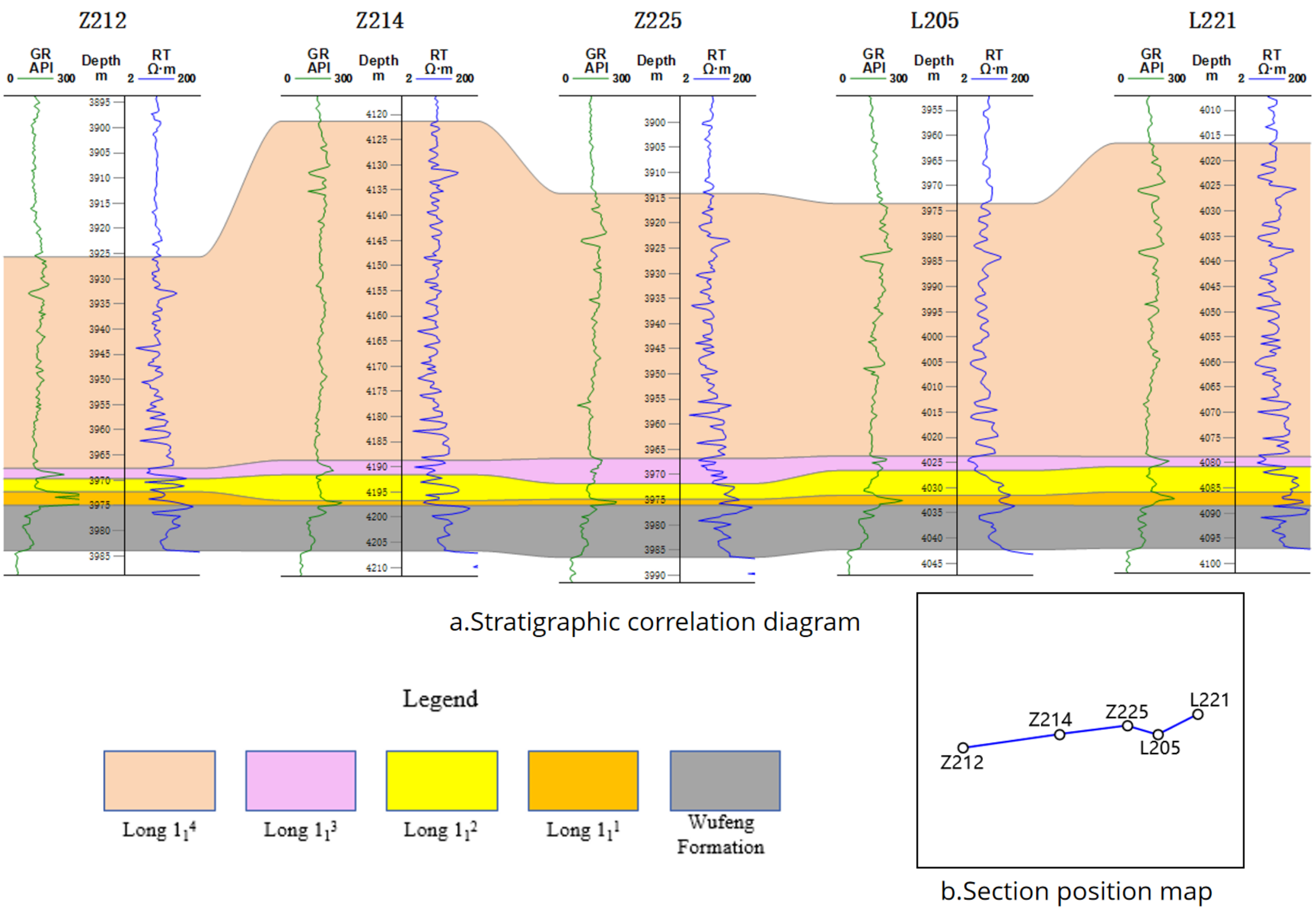


Figure 3. The east-west stratigraphic comparison map of the Wufeng Formation - Long 11 submember in the Z205 well area.

conducive to increasing the extension distance of fractures and forming complex fracture networks [15–19]. Through these four types of parameters, the reservoir is comprehensively classified and evaluated from four aspects: the quality of hydrocarbon source rocks, physical properties, gas-bearing capacity, and rock mechanical characteristics.

4.2.1 *Application of the TOPSIS Algorithm*

TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) is a widely used multi-attribute decision-making analysis method. This method can avoid the subjectivity of data and can also well depict the comprehensive influence strength of multiple influencing indicators. The basic idea is to list the comprehensive evaluation issues in a matrix, determine the positive ideal solution and negative ideal solution through matrix normalization, then calculate the Euclidean distance between each evaluated object and the positive ideal solution and negative ideal solution, and compare the degree of closeness of different evaluated objects to the positive and negative ideal solutions, thereby making a comprehensive evaluation ranking. In this model, the positive ideal solution represents the situation where all the index attributes reach the most satisfactory state, while the negative ideal solution indicates the scenario where all the index attributes reach the least satisfactory state [20–24].

4.2.2 *Construct a Decision-making Matrix for Reservoir Evaluation*

As mentioned in the previous text, TOC, porosity, gas content, and brittle minerals all have a significant impact on the quality of shale gas reservoirs. In this study, these four types of reservoir parameters were still selected as the core parameters for reservoir evaluation, and a decision matrix X^0 was constructed:

$$X^0 = (x_{ij}^0)_{n\times m} = \begin{bmatrix} x_{11}^0 & x_{12}^0 & \cdots & x_{1m}^0 \\ x_{21}^0 & x_{22}^0 & \cdots & x_{2m}^0 \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1}^0 & x_{n2}^0 & \cdots & x_{nm}^0 \end{bmatrix} \quad (1)$$

where x_{ij}^0 $(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m)$ represents

Table 1. Reservoir parameter table of the Wufeng formation - long 11 submember.

Formation	Member	Submember	Microlayer	TOC (%)	Porosity (%)	Gas content (m^3/t)	Brittle mineral (%)	Young modulus (GPa)	Pois	Horizontal stress difference (MPa)
Longmaxi Formation	Long 1 Member	Long 11 Submember	Long11[4]	2.3~3.2	4.3~6.0	2.4~6.7	51.7~63.1	30.1~50.6	0.208~0.285	12.2~13.8
				2.7	5.3	4.6	58.0	36.2	0.228	13.0
			Long11[3]	3.2~5.0	4.2~6.9	3.9~11.0	53.9~75.8	31.5~40.6	0.197~0.240	12.4~13.7
				4.0	5.7	7.2	66.3	35.4	0.219	13.0
			Long11[2]	3.7~4.9	3.5~6.2	6.6~8.7	68.2~83.6	38.0~45.3	0.192~0.206	12.9~13.5
				4.4	5.0	7.7	77.1	42.6	0.201	13.3
			Long11[1]	4.0~7.3	3.6~6.4	7.6~10.6	60.4~78.7	41.0~43.3	0.196~0.225	12.9~13.9
				5.2	4.9	8.7	72.0	42.0	0.211	13.5
			Average of the Long11[1]-Long11[3]	3.2~7.3	3.5~6.9	3.9~11.0	53.9~83.6	31.5~45.3	0.192~0.240	12.2~13.9
				4.5	5.2	7.6	71.8	39.1	0.211	13.2
Wufeng Formation				1.6~3.3	2.8~4.7	0.2~11.5	69.4~83.8	35.3~58.5	0.202~0.282	12.7~13.9
				2.3	3.8	6.0	74.4	43.1	0.228	13.4

the original value of the j-th evaluation indicator in the i-th row.

Before conducting the TOPSIS calculation, it is generally necessary to perform "positive transformation" on the data, that is, the larger the indicator value, the better the evaluation result. Since the TOC content, porosity, gas content, and brittle minerals are all theoretically larger, and the reservoir quality is better when these parameters are larger, there is no need for "positive transformation" in this calculation.

Meanwhile, different evaluation indicators often have different units of measurement and dimensions. Such a situation can affect the results of data analysis. To eliminate the influence of the dimensions between the indicators, data needs to be standardized. This paper uses the range method to process the data, and the specific formula is:

$$x_{ij}^1 = \frac{x_{ij}^0 - \min_i(x_{ij}^0)}{\max_i(x_{ij}^0) - \min_i(x_{ij}^0)} \tag{2}$$

where x_{ij}^1 $(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m)$ represents the standardized value of the j-th evaluation index in the i-th row; x_{ij}^0 represents the original value of the j-th evaluation index in the i-th row; $\min_i(x_{ij}^0)$ and $\max_i(x_{ij}^0)$ respectively represent the minimum and maximum values in the j-th column.

After applying the range method, the standardized decision matrix X^1 was obtained:

$$X^1 = (x_{ij}^1)_{n\times m} = \begin{bmatrix} x_{11}^1 & x_{12}^1 & \cdots & x_{1m}^1 \\ x_{21}^1 & x_{22}^1 & \cdots & x_{2m}^1 \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1}^1 & x_{n2}^1 & \cdots & x_{nm}^1 \end{bmatrix} \tag{3}$$

4.2.3 *Calculate the Positive and Negative Ideal Solutions and the Euclidean Distance*

After the standardization process, the decision matrix X^1 contains all extremely large data. Based on these data, the positive and negative ideal solutions can be constructed.

Positive ideal solution:

$$\begin{aligned} Z^+ &= [z_1^+, \cdots, z_j^+, \cdots, z_m^+] \\ &= [\max\{x_{11}^1, \cdots, x_{n1}^1\}, \cdots, \max\{x_{1j}^1, \cdots, x_{nj}^1\}, \\ &\quad \cdots, \max\{x_{1m}^1, \cdots, x_{nm}^1\}] \end{aligned} \tag{4}$$

Negative ideal solution:

$$\begin{aligned} Z^- &= [z_1^-, \cdots, z_j^-, \cdots, z_m^-] \\ &= [\min\{x_{11}^1, \cdots, x_{n1}^1\}, \cdots, \min\{x_{1j}^1, \cdots, x_{nj}^1\}, \\ &\quad \cdots, \min\{x_{1m}^1, \cdots, x_{nm}^1\}] \end{aligned} \tag{5}$$

Calculate the distance between the quality of each reservoir and the positive and negative ideal solutions.

The distance from the positive ideal solution:

$$D_i^+ = \sqrt{\sum_{j=1}^{m}(Z_j^+ - x_{ij}^1)^2} \tag{6}$$

The distance from the negative ideal solution:

$$D_i^- = \sqrt{\sum_{j=1}^{m}(Z_j^- - x_{ij}^1)^2} \tag{7}$$

However, in actual reservoir evaluation, the importance of different evaluation parameters such as TOC content, porosity, gas content, and brittle minerals varies. For instance, TOC content is an important indicator as it can reflect the hydrocarbon generation potential and storage capacity of shale gas reservoirs, thereby determining the gas content of the shale gas reservoirs. It is the foundation of shale gas exploration and development. This paper refers to the reservoir evaluation experience of the Sichuan Basin (Table 2), and incorporates the subjective weight coefficients into the model construction, so that the final evaluation results can simultaneously incorporate subjective experience judgment, objective evaluation information and reservoir differences.

Table 2. Subjective weight table of evaluation parameters for reservoirs of the Wufeng Formation - Long 11 submember in the Sichuan basin.

Reservoir parameter	TOC	Porosity	Gas content	Brittle mineral
Reight coefficient	0.3	0.2	0.3	0.2

Let the subjective weight vector obtained from the reservoir evaluation experience in the Sichuan Basin be $\omega = (\omega_1, \ldots, \omega_r, \ldots, \omega_n)$. Then, the distance between the reservoir quality combined with subjective weights and the positive and negative ideal solutions is:

$$D_i^+ = \sqrt{\sum_{j=1}^{m}\alpha_j(Z_j^+ - x_{ij}^1)^2} \tag{8}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m}\alpha_j(Z_j^- - x_{ij}^1)^2} \tag{9}$$

4.2.4 Calculate the Relative Progress of the Project

The relative deviation ratio C_i between the reservoir quality and the ideal solution is:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{10}$$

The larger the C_i value is, the better the reservoir quality will be; conversely, it will be worse. The evaluation parameters of the reservoir in the Wufeng Formation - Long 1_1 submember of the well area are calculated based on C_i and the optimal reservoir can be determined according to the size of C_i.

4.3 Reservoir Classification

Using the TOPSIS algorithm, the evaluation parameters C_i of the reservoir layers of the Wufeng Formation - Long 1_1 submember in the Z205 well area were calculated. Meanwhile, based on the actual reservoir conditions of the well area, the following classification was defined: when $C_i \geq 0.6$, it is classified as Class I reservoir; when $0.4 \leq C_i < 0.6$, it is classified as Class II reservoir; when $0.2 \leq C_i < 0.4$, it is classified as Class III reservoir; when $C_i < 0.2$, it is classified as non-reservoir (Table 3).

4.4 Reservoir Distribution Characteristics

The reservoir evaluation results of the appraisal wells in the Z205 well area indicate that the Wufeng Formation - Long 1_1 submember of this area mainly consists of Class I and Class II reservoirs, while Class III reservoirs are not developed. The Class I reservoirs are mainly located in the Long 1_1^1 to Long 1_1^3, and the bottom of the Long 1_1^4. The Class II reservoirs are mainly distributed in the Long 1_1^4, and the Wufeng Formation occasionally occurs. The Class III reservoirs are mainly distributed at the top of the four small layers and the Wufeng Formation (Figure 4).

The Wufeng Formation - Long 1_1 submember of the well area has at least three stable and well-distributed layers of Class I continuous reservoirs vertically, as shown in Table 4. The No. ① Class I continuous reservoir is widely distributed throughout the Z205 well area and its distribution is stable. It mainly occurs in the Long 1_1^1 to Long 1_1^3, and the bottom of the Long 1_1^4, with a thickness ranging from 8.9 to 22.3m. Its thickness is greater than that of No. ② and No. ③. The central part of the well area (Huliongchang syncline, Gaoshikuan syncline, and the northern part of Panlongchang syncline) is the most developed, with the maximum thickness, and gradually thins from south to north. The No. ② Class I continuous reservoir is mainly distributed in the middle part of the Long 1_1^4, with a thickness ranging from 3.3 to 9.9m. It is most developed in the Gaoshikuan syncline and gradually thins as it moves southward and northward. The No. ③ Class I continuous reservoir is distributed in the upper part of the Long 1_1^4. The overall thickness

Table 3. Classification and evaluation of reservoirs in the Wufeng Formation - Long 1_1 submember in the Z205 well area, based on C_i values.

Reservoir types	Class I reservoir	Class II reservoir	Class III reservoir	Non-reservoir
Range of C_i values	$C_i \geq 0.60$	$0.4 \leq C_i < 0.60$	$0.2 \leq C_i < 0.40$	$C_i < 0.20$

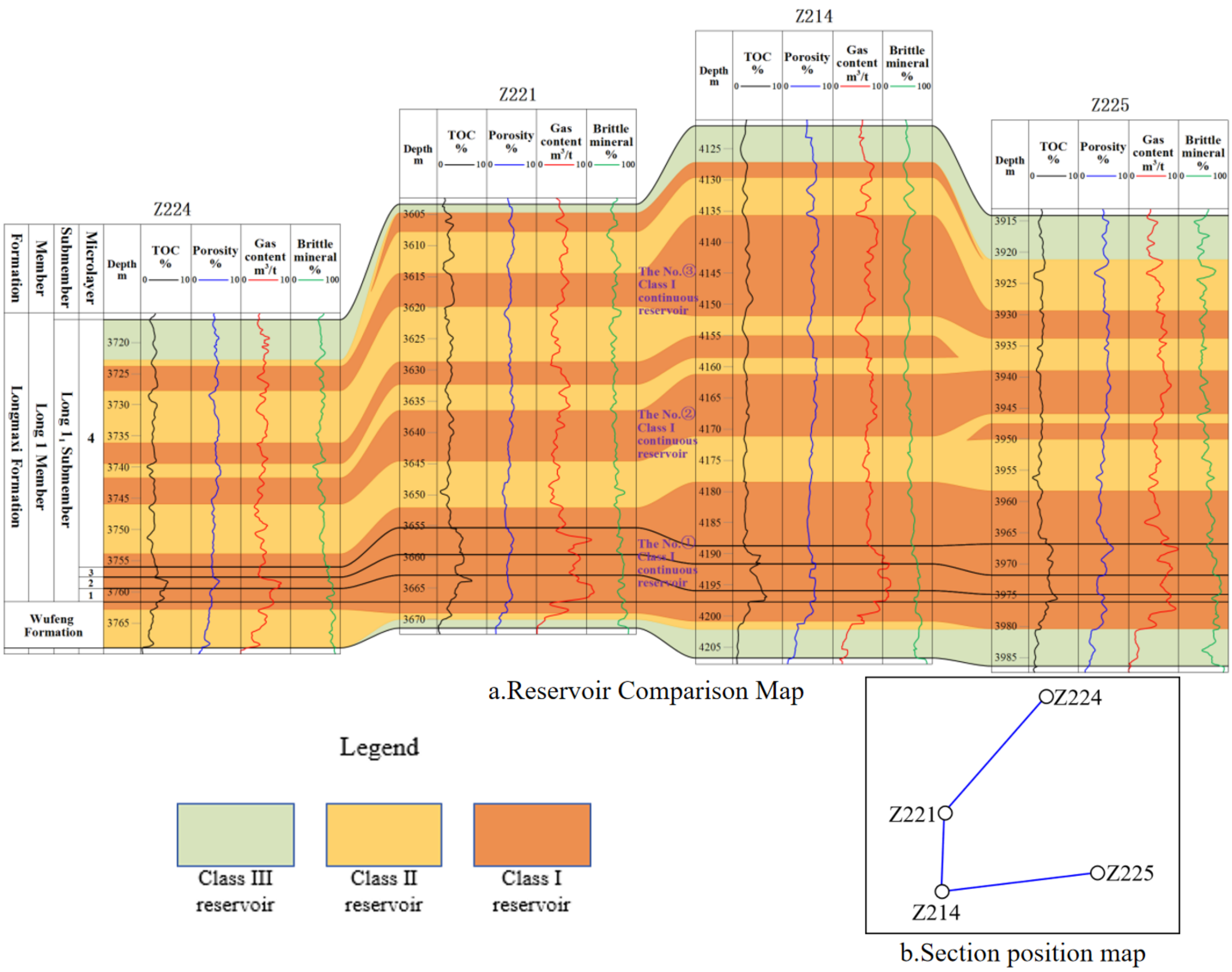


Figure 4. The reservoir distribution map of the Wufeng Formation - Long 11 submember in the Z205 well area.

Table 4. The statistical table of continuous thickness of Class I rock units from the Wufeng Formation to Long 1_1 submember (Nos. ① to ③) in the Z205 well area.

Wells	Z224	Z221	Z214	Z225	Z213	Z215
The No. ① Class I continuous reservoir (m)	8.9	16.9	22.3	22.1	13.9	12.3
The No. ② Class I continuous reservoir (m)	4.2	8.1	9.9	6.9	3.3	0
The No. ③ Class I continuous reservoir (m)	3.9	5.3	16.1	4.4	2.3	0

is relatively thin, ranging from 2.3 to 16.1m. It is most developed in the Gaoshikuan syncline, with a thickness of up to 16.1 meters (at Well Z214), and gradually thins from south to north.

Based on the longitudinal development characteristics and lateral distribution patterns of Class I reservoirs in the Z205 well area, three stable and well-distributed sets of Class I continuous reservoirs have been developed vertically in the well area. The optimal reservoirs are mainly developed in the Long 1_1^1 to Long 1_1^3. On the horizontal plane, they are mainly distributed in the Huilongchang syncline, Gaoshikuan syncline, and the northern part of Panlongchang syncline. From south to north, the Class I reservoirs gradually thin out.

5 Conclusion

(1) The variation patterns of the thickness of each sublayer in the Wufeng Formation - Long 1_1 submember of the Z205 well area vary significantly in different directions. The total thickness of the main reservoir layers from Long 1_1^1 to Long 1_1^3 is 5.6 to 10.0m. As a whole, it shows a gradually increasing trend from north to south and from west to east.

(2) By using the TOC content, porosity, gas content, and brittle mineral content, and employing the TOPSIS algorithm, while also based on the evaluation experience of shale gas reservoirs in the Sichuan Basin and combined with subjective weights and objective analysis, a shale gas reservoir evaluation model for the Wufeng Formation - Long 1_1 submember in the Z205 well area was established.

(3) In the Z205 well area, three sets of stable and planarly distributed Class I continuous reservoirs are vertically developed in the Wufeng Formation - Long 1_1 submember. The No. ① Class I continuous reservoir is mainly distributed in the Long 1_1^1 to Long 1_1^3, and it is the main productive layer of the well area. The No. ② and No. ③ Class I continuous reservoirs are mainly developed in the Long 1_1^4, and can serve as the successor areas for subsequent shale gas exploration and development. They have the prerequisite conditions for three-dimensional development, and the resource potential of the well area is enormous.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

All authors are employees of the Institute of Geological Exploration and Development, CNPC Chuanqing Drilling Engineering Company, Chengdu 610051, China. The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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