

# Analysis of the Main Geological Controlling Factors for the High Production of Shale Gas Horizontal Wells in the Sichuan Basin

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**Abstract:** Shale gas in the Sichuan Basin is in the stage of large-scale exploitation. Considering technical factors, the geological factors affecting the production of shale gas horizontal wells can be analyzed according to related mining practice cases in the area, and the geological information and logging data related to the shale gas horizontal wells can be analyzed in detail. Then, the horizontal wells can be divided into levels on this basis to better find out core factors that restrict the productivity of shale gas wells and then conduct comprehensive evaluation. It is necessary to make full use of the results obtained from the research to find out the geological characteristics of high-yield horizontal wells, so as to provide support for drilling operations and continuously improving the production of horizontal wells.

## 1. Introduction

Changning and Weiyuan in Sichuan are national-level shale demonstration areas. The application of drilling, fracturing and other technologies can increase production in shale mining. However, there are also differences in production capacity under the increasingly mature environment of mining technology, which can be mainly attributed to geological factors. Based on the geological information and logging data of shale gas horizontal wells, it is practical to compare and analyze horizontal wells with the same technology and management system but different geology, so as to clarify the characteristics of reservoir distribution and then explore the high-yield geological model of shale gas horizontal wells.

## 2. Background Introduction of the Case

The Changning and Weiyuan shale gas wells lay in the southern part of the Sichuan Basin, in the low and gentle structural zone. The rise of temperature led to the rise of the foundation, causing the sea level to rise rapidly. Under that background, widespread sedimentary phenomena appeared in the Sichuan Basin, and high-quality marine shale gradually developed. They are located in the lower Rudanian strata of the Wufeng Formation, with a thickness between 25 and 40 m, and they belong to the key strata of shale mining in the Sichuan Basin. The information data of coring wells in this area is selected to analyze their sequence stratigraphy, reservoir parameters, biological evolution and electrical characteristics. The high-quality shales of the Longyi Section in the Wufeng Formation were divided into 5 layers from bottom to top (Longyi Layer 1~5) to indicate the presence of siliceous shales. The GR curve of logging is “funnel-shaped”, gradually increasing upward, and the curve value is between 178 and 220 API. The logging GR curve of Guanyinqiao Section is “concave”, ranging from 40 to 100 API. The GR curves of the remaining 4 layers from bottom to top are “convex, concave, convex, and concave” respectively. The GR value of Layer 1 is the highest, between 280~400 API; The GR curve of Layer 2 is slightly lower, and that of Layer 4 is the lowest. After comparing the geological phenomena in various regions, there are no missing phenomena at different levels, but non-uniform characteristics are obvious. The thickness of Weiyuan Section B is lower than that of the 5th group of Changning District and Weiyuan Section A; at 5m of the Weiyuan well area is the Longyi Layer 1, which is thicker than the Changning area, and its height is 1.7m; at 7m in Changning District is Longyi Layer 2 and Longyi Layer 3, and the actual thickness exceeds that in Weiyuan District, specifically 25m; the Changning well area is 13m

thick, which is about twice as thick as it <sup>[1]</sup>.

The actual drilling materials for horizontal wells were selected and put into production in the work area, with a total of 90 wells. Starting from the horizontal section, the researchers divided the levels, obtained the data of each layer, understood the distribution relationship and comprehensively observe the core and outcrop positions according to the difference in the trajectory of these horizontal wells. It can be seen from the relevant data that there are more horizontal bedding in the shale formation. This feature is very similar to the characteristic of small layers of rocks in terms of sedimentary structures, biological distribution, and mineral species. The existence of this feature makes the shale be regarded as a marker layer in the oil and gas exploration process, and the stratum is tracked and referenced in layers. After completing the establishment of the geological and structural recovery related models of the horizontal wells, the small horizontal wells are divided into layers based on the logging data to confirm the characteristics of trajectory. Due to that there are only a few core wells in the current production area, it is difficult to solve the problem of dividing thin layers based on the evaluation information of horizontal wells.

Related analysis showed that the average length of shale horizontal wells in Changning District is 1500m. According to the tests conducted on horizontal wells, there are 24 wells with a production exceeding  $15 \times 10^4 \text{ m}^3/\text{d}$ , among which the length of Longyi Layer 1 is the longest, with an average value of 650m; which ranks the second is the Wufeng Group, with an average of 208m. The Longyi Layer 1 in Changning District is 1.7m thick and is the largest in length. Drilling-encounter for this layer shows that the horizontal section is 156m long. In the Wufeng Formation, the drilling-encounter length of Longyi Layer 1 is more than 1000m, while that of Longyi Layer 2 and Longyi Layer 4 is 400m long, respectively. According to the logging test in the Weiyuan District, the production of 33 wells is more than  $15 \times 10^4 \text{ m}^3/\text{d}$ , and each layer is 1100m; Zone A and Zone B are 1115m and 1107m respectively, which are both longer than the drilling-encounter length of the Layer 2; the length of Zone A is 364m, and that of Zone B is 319m. In addition, the roadway of horizontal wells in Weiyuan District is lower than those in Changning District. The weighted average method can be used to calculate the actual distribution of the vertical target at the entrance and exit of the horizontal well. There are two wells in the Changning area, which are located in the middle of the Wufeng Formation, and their production ranges from  $15 \times 10^4$  to  $20 \times 10^4 \text{ m}^3/\text{d}$ . There is no horizontal well target in the Layer 1, and the Layer 2 has the most targets, with 14 wells in total, and the production of each is higher than  $20 \times 10^4 \text{ m}^3/\text{d}$ . There are 28 wells in the middle of the target at the Layer 1 in the Weiyuan District, with a production rate of more than  $20 \times 10^4 \text{ m}^3/\text{d}$ .

### 3. Analysis of the Characteristics of Shale Reservoirs

Because the quality of shale reservoirs is directly related to the production of gas wells, there are relatively many factors that affect the reservoirs. If it is in an area with relatively similar geological structures, the gas generation potential, fracturing property, gas-bearing property and reservoir physical properties are the main factors affecting the structure of shale reservoirs. For the high-yield reservoirs of the horizontal wells in the above regions of Changning and Weiyuan, the output exceeds  $15 \times 10^4 \text{ m}^3/\text{d}$ . It can be seen from the distribution characteristics that the TOC exceeds 3%, so it can be concluded that they are high-quality shales. In the horizontal wells in Changning District, there are many situations in drilling-encounter Wufeng Formation and Layer 2, and at the same time, the GR value is lower than that of Layer 1. The TOC of horizontal wells is 3.8%, and the TOC values of drilling-encounter Weiyuan Zone A and Zone B in the Layer 1 are 5.1% and 4.3%, respectively. Simply comparing the parameters of the Layer 1, the Weiyuan District is lower than the Changning District.

In the drilling-encounter stage of horizontal wells, the TOC content in Layer 1 is higher than that of all overburden layers, which is consistent with the characteristics of vertical wells. After comparison, there is no obvious difference in porosity between Changning and Weiyuan, both of which are between 6% and 8%. The total gas content of the three well zones exceeds  $6 \text{ m}^3/\text{t}$ . If the burial depth continues to increase, the gas volume of Weiyuan Zone B will exceed that of Changning District and Weiyuan Zone A. The content of various minerals such as siliceous and

carbonate rock can affect the effect of hydraulic fracturing, and the content of a few substances and the content of clay are inversely proportional. After comparison, it is concluded that the brittle minerals in the Changning District account for 72.5%, and the contents of the Weiyuan Zone A and Zone B are 69% and 63%. Relatively speaking, the clay content of Weiyuan Zone B is more than 35%, which is the highest. According to the reservoir evaluation parameters and the productivity of horizontal wells, shale storage can be classified into levels. The specific information is shown in Table 1:

Classification	TOC	Brittle minerals	Effective porosity	Total air content
I	$\geq 3\%$	$\geq 55\%$	$\geq 5\%$	$\geq 3\text{m}^3/\text{t}$
II	2~3%	45~55%	3~5%	2~3 $\text{m}^3/\text{t}$
III	1~2%	30~45%	2~3%	1~2 $\text{m}^3/\text{t}$

The Layer 1 of Changning District has the highest TOC and total gas content, and Type I reservoirs are developed throughout the entire section with low thickness; The parameters of the 1st and 2nd thin layers are roughly the same, and they belong to Type I reservoirs with a large thickness; there are Type I reservoirs in the upper part of Wufeng Formation. The upper part of Wufeng Formation and the 1st and 2nd thin layers in Changning District can be called Type I reservoirs, with a thickness of 12m. There are differences in the reservoirs in the Changning and Weiyuan areas. Only the Layer 1 has good parameters, and it belongs to Type I reservoirs with a thickness of 5m<sup>[2]</sup>.

Horizontal wells have strong lateral heterogeneity when drilling encounter shale, and to ensure that the fracturing effect can be reflected, it is necessary to clarify the discontinuous distribution of high-quality reservoirs -- The continuous distribution of effective reservoirs should exceed 25m, and if it is less than this index, it is regarded as an interlayer section. The drilling-encounter rate of Type I reservoirs in the Changning District can exceed 65%; the drilling-encounter rate of Type I reservoirs in Weiyuan Zone A can reach 63%, and it can reach 60% in Zone B. The drilling-encounter rate of Type I and Type II reservoirs is obviously lower than that of Changning District. Reservoir type and distribution characteristics are important information for target confirmation; Layer 1 and Layer 2 of Changning District are mainly Type I reservoirs; the Type I reservoirs of the 1st thin layer present 81.3% and that of the 2nd thin layer accounts for 70.6%. The total amount of Type I and Type II reservoirs is higher than 90%. In the 3rd thin layer of the Wufeng Formation, Type I reservoirs account 40%, mostly located on the top of the 3rd thin layer and the top of the Wufeng Formation. Type I reservoirs in the Weiyuan area are concentrated in Layer 1, with a content of more than 70%; the total amount of Type I and Type II tends to 90%, and Type I reservoirs are less than 30% in the 2nd and 3rd thin layers. Therefore, a barrier is formed between them and the Wufeng Formation, which increases the difficulty of horizontal well steering.

#### 4. Analysis of Factors Affecting the Productivity of Gas Wells

The geological burial depth of the Changning and Weiyuan gas field development areas is moderate with a gentle structure, and the burial depth is between 2500 and 3800m. Therefore, the degree of thermal evolution of geology is relatively high, exceeding 2.8%. Geology is an important factor affecting the production of shale gas fields. At the same time, the fault system, the direction of the in-situ stress, and the orientation of the horizontal well are all core factors that affect the production of the gas field. Faults have an enrichment effect, which will affect the preservation of shale gas. However, the impact of medium and small faults on rock and gas is not significant. There are small inverse faults in the Longma Formation in the developing layer of Changning District. Selecting the horizontal section of the production well as the research object, it can be judged that the distance between the gas field and the nearest fault is 0.1~1.45km; the fault distance is within 30m, and the main components include fracture zones and small-scale faults. The average production value of the production wells can reach 22×104m<sup>3</sup>/d, which means that the small fault belongs to the weak surface of the producing layer, and that complex fractures may occur in the fracturing stage of the reservoir. Therefore, the production capacity of shale gas there can be increased to a certain extent.

In Changning and Weiyuan, the highest horizontal stress is in the near east-west direction, while

the horizontal wells in Changning District and Weiyuan Zone A are near the north-south direction. There are two modes of well deployment in Weiyuan Zone B, namely in the direction of “near north-south” and “north-west-south-east”. Taking the bore depth of the wellhead on the north side of Weiyuan Zone B as the research object and the reservoir drilling-encounter rate and parameters close to the well for analysis, the productivity of the wells in the “near north-south” direction exceeds that of the “north west-south east” wells. The north-south horizontal wells are the gas wells with the highest production in Zone B and the unit production can reach  $1.2 \times 10^8 \text{m}^3$ , which can also be explained that the vertical well layout and the maximum horizontal stress can increase the production capacity of horizontal wells <sup>[3]</sup>.

In addition, the analysis of the impact of buried depth can focus on the analysis of the distribution characteristics of the reservoir from the perspective of the difficulty of construction. In Weiyuan Zone B, the static parameters of 40 wells in Wufeng Formation and Layer 1 and Layer 2 were counted. If the burial depth is less than 500m and the difference is not high, the influence of porosity mineral content, TOC and other factors on the productivity of the shale gas well can be ignored.

## **5. Core Geological Factors Affecting the High Production of Shale Gas Wells**

### **5.1 The Best Target and the Length of the thin Layer**

Because the middle and upper parts of the Wufeng Formation and 1st and 2nd thin layers belong to Type I reservoirs in the Changning District, there are the best targets for high-yield wells in the 1st and 2nd thin layers. At the same time, the bottom of the target body and the high-quality shale are close to each other. Therefore, more Type I reservoirs are produced after fracturing communication, so that the production of oil wells is high. It can be seen that in the high-yield wells in the Changning District, the best position of the target is in the area 3~8m from the bottom of the shale. In Weiyuan District, the target of high-yield wells is located in the Layer 1, and there is an optimal high-yield target area in the 0~5m area at the bottom of Layer 1. It can be concluded from analysis that the production of horizontal wells in Changning District is directly related to the drilling-encounter length of Layer 1 and Layer 2. When the horizontal well is in this layer with a higher proportion of crossing, the higher the yield is obtained, and thus the production effect is better. According to the test the production effect of the production well in Changning District, the production exceeds  $20 \times 10^4 \text{m}^3/\text{d}$ ; the drilling-encounter length of the Layer 1 and Layer 2 is supposed to exceed 900m. The production of horizontal wells in Weiyuan District is related to the drilling-encounter length of Layer 1. In order to obtain high production, the lower limits of the drilling-encounter length in well Zone A and Zone B were set to 1100m and 1200m, respectively.

In addition to the similar control mode of shale gas fields, the sedimentary background, shale reservoir parameters, and distribution characteristics of the mining layers in the Sichuan Basin are also very similar. If the target of a horizontal well sinks into Layer 1 and Layer 2, its production will be higher than that of the target in the overlying layer and also higher than the well below the Wufeng Formation.

### **5.2 Drilling-Encounter Rate of Effective Shale Reservoirs**

If the engineering process is similar, there is a positive correlation between the drilling-encounter rate and well production in Type I reservoirs. For mixed reservoirs containing Type I and Type II reservoirs, there is no obvious correlation between the drilling-encounter rate and gas well productivity. This is because when a reservoir is classified into Type II, its limit value is set low; the TOC in most horizontal well reservoirs is more than 3%, and the content of brittle materials is more than 55%. By coring the vertical wells and observing the lithology of Type II reservoirs, it is judged whether it is under-developed. It can be seen that the mud content in the inorganic pores is relatively high; the existence of such factors may have impacts on Type II reservoirs, leading to the fact that their gas-bearing, gas generation potential and fracturing properties may be lower than those of Type I reservoirs <sup>[4]</sup>.

The actual production of horizontal wells in Changning District and the drilling-encounter rate of Type I reservoirs show a good correlation, followed by the correlation between the wells in Weiyuan Zone A and Zone B. To obtain high-yield wells, the output should reach  $20 \times 10^4 \text{ m}^3/\text{d}$ . The lowest drilling-encounter rate of type I reservoirs in horizontal wells in Changning District is 60%, that is, when the length of the horizontal section is 1500m, the specific length of drilling-encounter of Type I reservoirs can exceed 900m. In Weiyuan Zone A and Zone B, the drilling-encounter rate of type I reservoirs is expected to reach 65%~70%, that is, when the horizontal length is 1500m, the length from drilling-encounter of Type I reservoirs should be between 950m and 1050m.

### 5.3 High-Yield Geological Model

In Changning and Weiyuan demonstration areas, there are several main factors affecting the geology of high-yield horizontal wells: the positioning of the optimal target, confirmation of the drilling-encounter length of the dominant layer, and the drilling-encounter rate of Type I reservoirs. The importance of the above factors can be sorted by means of gray correlation and analytic hierarchy process, so as to obtain the geological influence factors of the high-yield wells in Changning District. From high to low they are the optimal target (45%), the dominant layer drilling-encounter (30%), and the reservoir drilling-encounter (25%). The production mode of high-yield wells can be formulated according to the geology of this area. For example, drilling high-quality target areas Layer 1 and Layer 2 into the well and ensuring the smoothness of the drilling trajectory can ensure a good drilling-encounter rate for Type I reservoirs, thereby increasing the output of single wells.

If the middle of the target body is 3~8m away from the high-quality shale bottom, and at the same time, the drilling-encounter length of Layer 1 and Layer 2 is between 900-1000m, the horizontal logging output will exceed  $20 \times 10^4 \text{ m}^3/\text{d}$ . The main factors affecting the geology of high-yield wells in the Weiyuan area are as follows: the drilling-encounter length of Layer 1 (45%), the best target (40%), and the drilling-encounter rate of the reservoirs (15%). Therefore, the high-yield drilling mode can be set like this: the well should pass through Layer 1 with smooth drilling trajectory, which can ensure the drilling-encounter rate of Type I reservoirs and improve the productivity of single wells; the length of the drilling-encounter in Layer 1 should be controlled between 1100 and 1200m; at this time, the distance between the middle of the target body and the bottom of the high-quality shale is 0~5m, so that the high-yield target of the horizontal well is easier to achieve<sup>[5]</sup>.

## 6. Conclusion

This research not only focused on the comprehensive analysis of the production conditions and production methods of some shale demonstration areas, but also summarized the geological elements that promote the high production of horizontal wells. It can be seen that the factors affecting the high production of horizontal wells in the Changning area are the length of the drilling-encounter of thin layers and the position of the target, and that the best target is at 3~8m below layer 1 and Layer 2 of high-quality shale. After testing, the output can reach  $20 \times 10^4 \text{ m}^3/\text{d}$ . In order to ensure the high production of shale gas wells, it is necessary to control the length of the horizontal section of the thin layer above 1000m, and the drilling-encounter rate for Type I reservoirs should exceed 60%. In the Weiyuan area, the factors affecting the production of shale horizontal wells are the location of the target and the length of the drilling-encounter of Layer 1, and the best target is within the Layer 1 and 0~5m away from the high-quality shale. Related test showed that the output of wells in Weiyuan Zone A and Zone B well can reach  $20 \times 10^4 \text{ m}^3/\text{d}$ . Therefore, the actual length of the horizontal section of the 1st thin layer in Zone A should be more than 1100m, and that of the 2nd thin layer in Zone B shall be more than 1200m; The drilling-encounter rate of Zone A and Zone B for Type I reservoirs should exceed 65% and 70%.

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