

# Determination of the Original Oil Saturation of the Chang 9 Oil Layer Group in the Zhouchang Oil Area of Wuqi Oilfield

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## Abstract

The original oil saturation of the reservoir is of vital importance for reservoir evaluation and calculation of geological reserves. To determine the original oil saturation of the reservoir and provide a reference for reservoir evaluation and geological reserve calculation, this paper takes the sandstone of the Chang 9 oil layer group in the Zhouchang oil area of Wuqi Oilfield in the Ordos Basin as the research object. Based on core, logging, mud logging and well testing data, combined with experimental data, four methods, namely the closed core method, mercury injection method, relative permeability method and logging interpretation method, are used to calculate the original oil saturation of the Chang 9 oil layer in the northeastern Wuqi area. The advantages and disadvantages of each method are analyzed to determine the original oil saturation that is suitable for the Chang 9 oil layer group in this area and thereby improve the accuracy of reserve calculation. The results show that the comprehensive logging interpretation method is the best method for calculating the original oil saturation in this area, and the original oil saturation is finally determined to be 54.6%.

## Keywords

Original Oil Saturation, Chang 9 Oil Layer Group, Closed Core Method, High-Pressure Mercury Injection, Archie Formula, Wuqi Oilfield, Ordos Basin

## 1. Introduction

In the field of petroleum geology and reservoir engineering, oil saturation is the core parameter to evaluate reservoir fluid distribution and development potential,

and its accurate determination is of great significance to reserve calculation, development plan formulation and recovery factor optimization (Camp, 2011; Ghanizadeh et al., 2015; Wang et al., 2016a). In recent years, with the extension of oil and gas exploration to complex reservoirs (such as low resistivity reservoirs, tight reservoirs and heavy oil reservoirs), the oil saturation measurement method faces many challenges, and it is urgent to improve its accuracy and applicability. The oil saturation value directly affects the calculation accuracy of the original oil geological reserves (OOIP). In reservoirs with low permeability, high salinity or strong heterogeneity, conventional methods (such as Archie's formula) often lead to errors due to simplified parameter assumptions or complex formation conditions. For example, due to the complex conductive mechanism of low-resistivity reservoirs, conventional logging interpretation is easy to overestimate water saturation and then underestimate oil saturation. In addition, the scarcity of sealed coring wells and the problem of fluid loss during core sampling further increase the difficulty of original oil saturation recovery. Therefore, based on core, logging, mud logging and oil test data, combined with experimental data, this paper uses four methods: closed coring method, mercury intrusion method, relative permeability method and logging interpretation method to calculate the original oil saturation of Chang 9 oil layer in the northeast of Wuqi area, and analyzes the advantages and disadvantages of each method. Considering various factors, the original oil saturation method of Chang 9 oil layer group suitable for this area is finally determined, which provides reference for subsequent reservoir evaluation and reserve calculation (Li, 2024; Li et al., 2024; Li, 2014; Wang, 2013; Zhang, 2016; Yang et al., 2010; Liu, 2013; Pan et al., 2000; Le, 2018; Zhu et al., 2021).

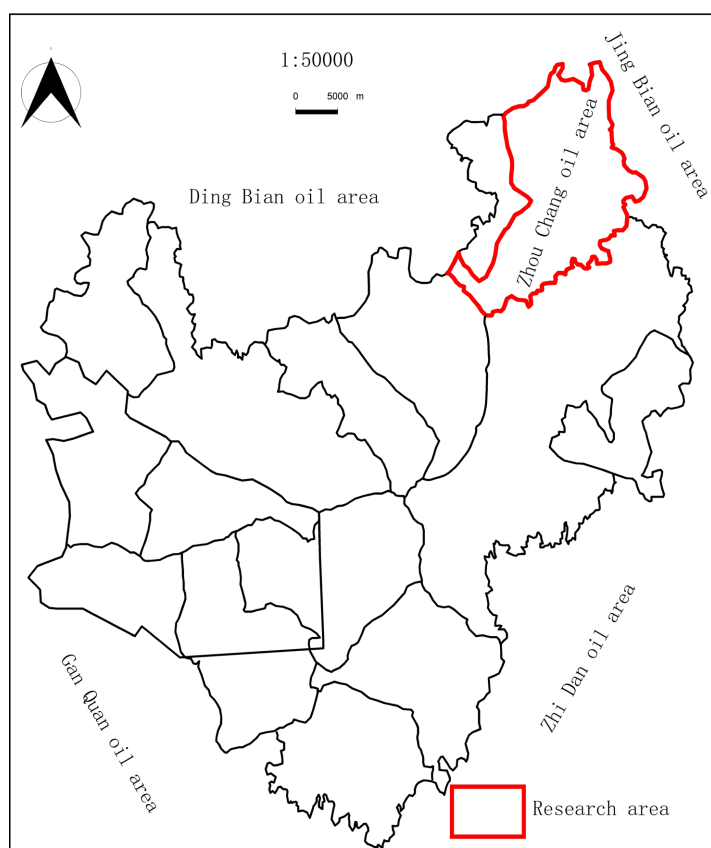
## 2. Regional Geological Overview

Ordos Basin is the second largest oil and gas-bearing basin in China. Multi-layer and multi-type mineral resources such as oil, gas, coal and uranium are very rich, and it is one of the largest energy production bases in China (Zhang, 2024). The Ordos Basin is located in the western part of the North China Platform, which can be subdivided into six first-order tectonic units: the northern Yimeng uplift, the western western thrust belt, the Tianhuan depression, the central Yishan slope, the eastern Jinxi flexural belt and the southern Weibei uplift. The faults and folds on the edge of the basin are more significant, showing the activity of its geological activities, while the internal structure of the basin is relatively simple, mainly based on the overall ascending and descending movement, lacking significant complex structures (Yang, 2002; He, 2003; Zhao & Liu, 1990; Guo et al., 1994).

The peripheral oil area of Wuqi area is located in the northeast corner of Wuqi oilfield in Ordos Basin. The east and west sides are Jing'an oilfield and Jiyuan oilfield respectively. The southwest is Wucangpu oil area of Wuqi oilfield. The length of north and south is about 24.6 km, the width of east and west is about 13.8 km, and the control area is about 325 km<sup>2</sup>. It belongs to the oil exploration and development zone under the jurisdiction of Wuqi oil production plant of Yanchang

oilfield (**Figure 1**).

The earliest exploration of the Zhouchang area began in June 2010, and its exploration and development are mainly divided into two stages. 1) Exploration and discovery stage: 2010-2011 is the exploration and discovery stage, and the Chang 2, Chang 7 and Chang 9 oil layers of the Yanchang Formation and the Yan 9 and Yan 10 oil layers of the Yan'an Formation were found. 2) Rolling development stage: from 2012 to 2015, through rolling expansion exploration. In 2012, the Chang 8 oil layer was found in Zhouchang 34 well, and the central, northern and eastern parts entered the mining stage. In the same year, the southern part of the study area increased exploration efforts, and then developed (Wang, 2021).



**Figure 1.** Geographical location of study area.

Since 2015, after 4 years of development and construction, the study area has fully entered the mining stage (Wang, 2021). According to the data of oil test and production test, it is considered that the Chang 9 oil layer group of Yanchang formation is one of the main layers in the Zhouchang oil area, which has great research significance.

### 3. Basic Characteristics of Reservoir

According to thin section data of 36 samples, the Chang 9 reservoir of Zhouchang

Oilfield in Wuqi area is mainly composed of feldspar quartz sandstone, followed by feldspar lithic sandstone, and the interstitial material is mainly filled with calcite, followed by chlorite and hydromica. The pore type is mainly intergranular pore, followed by dissolution pore, and the pore combination is dissolved pore-intergranular pore and intergranular pore-dissolved pore. The average pore diameter is 28.06  $\mu\text{m}$ , and the average throat diameter is 0.74  $\mu\text{m}$ , which belongs to the small pore fine throat type (Figures 2-4).

According to 195 gas data, the porosity of the study area ranges from 2.7 to 16.5%, with an average of 8.2%, and the permeability ranges from 0.04 to 3.08 mD, with an average of 0.46 mD (Figure 5 and Figure 6).

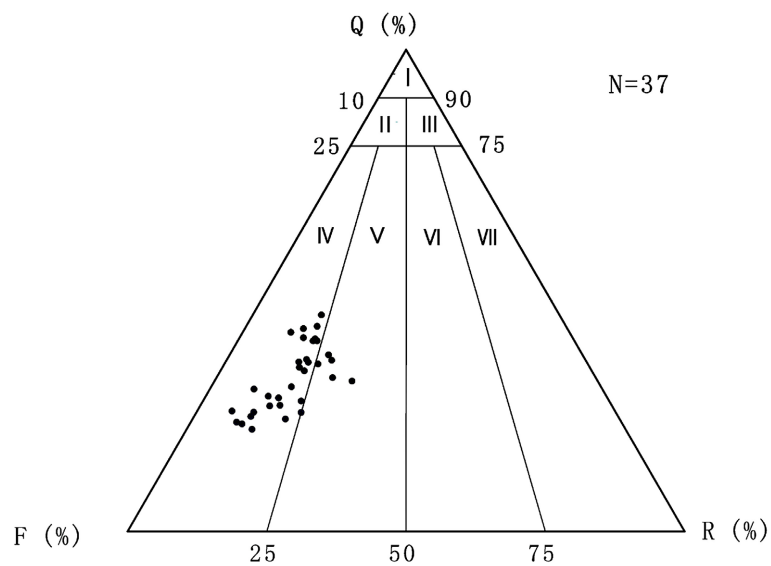


Figure 2. Triangular map of sandstone classification.

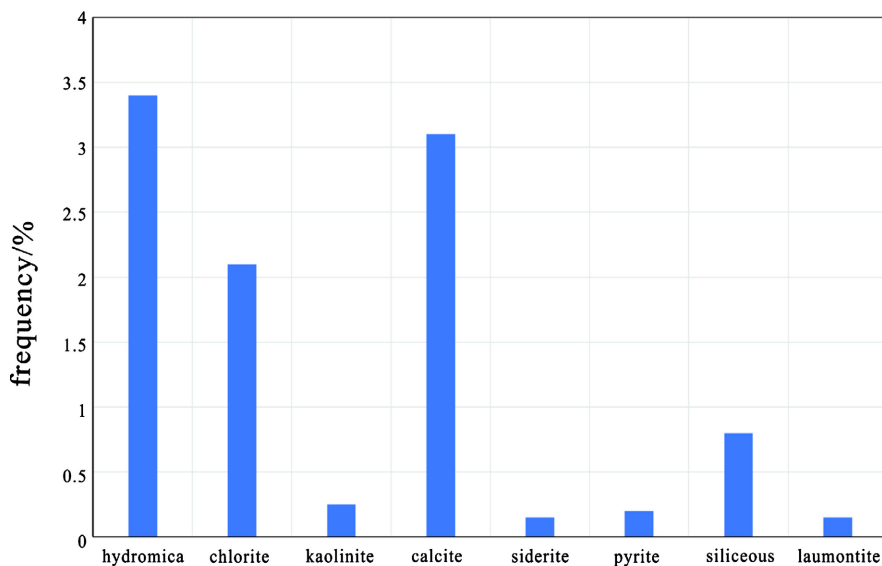


Figure 3. Interstitial content histogram.

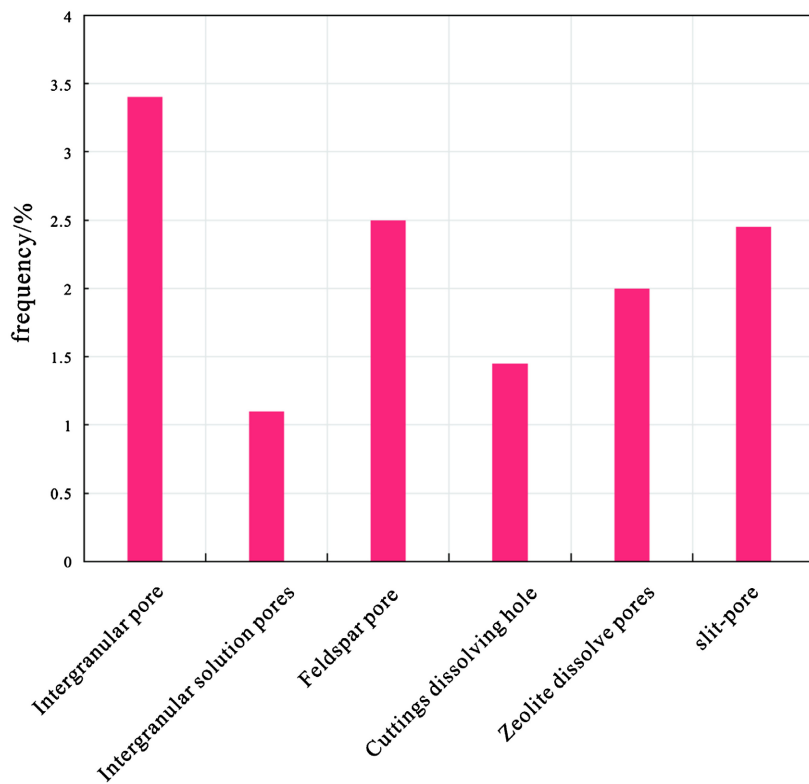


Figure 4. Pore type histogram.

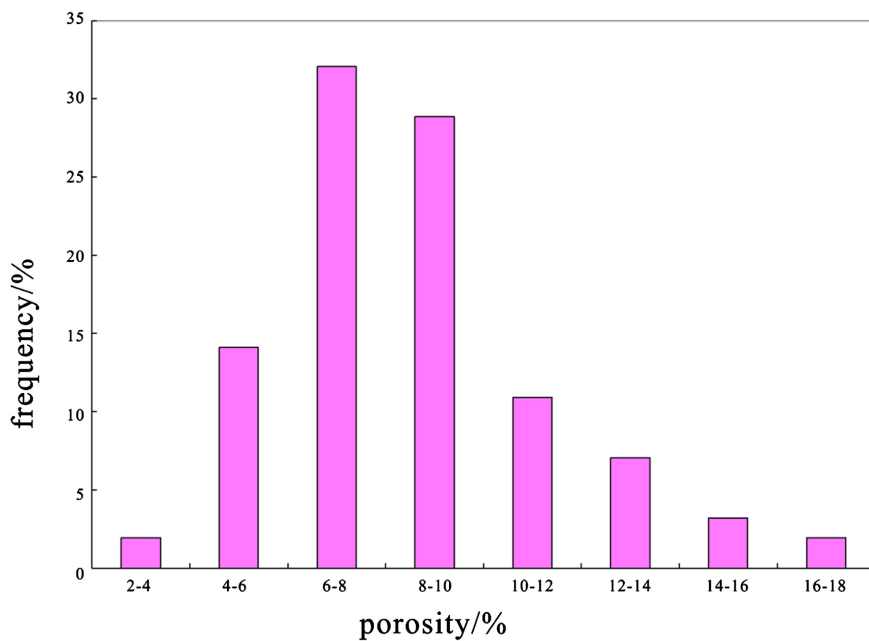
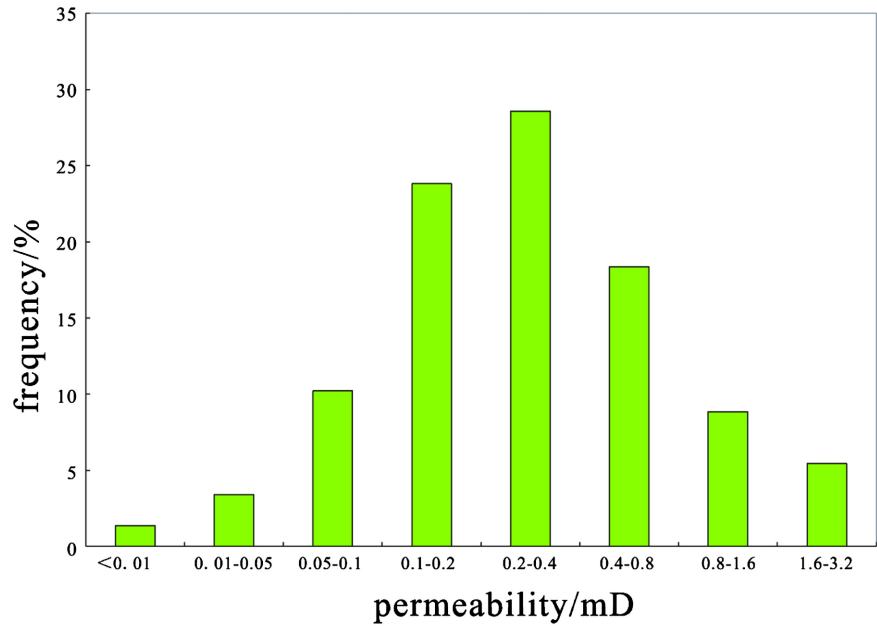


Figure 5. Sandstone porosity histogram.

According to the “oil and gas reserves calculation specification” (DZ/T 0217-2005), the Chang 9 reservoir group in the study area belongs to the ultra-low porosity and ultra-low permeability reservoir (Table 1 and Table 2).



**Figure 6.** Sandstone permeability histogram.

**Table 1.** “Oil and gas reserves calculation specification” (DZ/T 0217-2005)—Reservoir porosity classification table.

classification	Clastic rock porosity (%)	Non-clastic rock matrix porosity (%)
particularly high	≥30	
dhomosteroid	≥25 - <30	≥10
mid	≥15 - <25	≥5 - <10
cataphyll	≥10 - <15	≥2 - <5
very low	<10	<2

**Table 2.** “Oil and gas reserves calculation specification” (DZ/T 0217-2005)—Reservoir permeability classification table.

classification	Reservoir air permeability (mD)	Gas reservoir air permeability (mD)
particularly high	≥1000	≥500
dhomosteroid	≥500 - <1000	≥100 - <500
mid	≥50 - <500	≥10 - <100
cataphyll	≥5 - <50	≥1.0 - <10
very low	<5	<1.0

#### 4. Calculation of Original Oil Saturation

The original oil saturation refers to the oil saturation of the oil layer in the original state, which is not yet put into production. It refers to the percentage of the volume of crude oil in the reservoir in the original state to the effective volume.

When there is only oil and water in the pores:

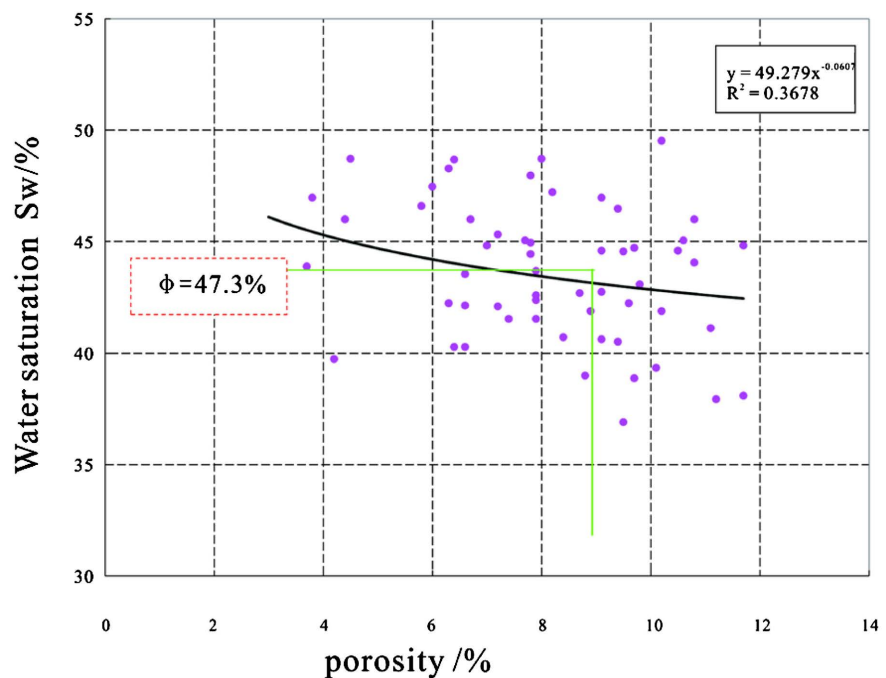
$$S_o = 100\% - S_w \quad (1)$$

In Equation (1):  $S_w$ —water saturation in oil layer (%),  $S_o$ —oil saturation in oil layer (%).

#### 4.1. Closed Coring Method

Closed coring is a technology to keep the core sample in a closed state during drilling. It is to prevent the fluid in the core from volatilizing or being polluted, and to maintain its original state, so as to analyze the physical and chemical properties of the formation more accurately. Its technology is mainly used in the exploration and research of oil and gas, such as porosity, permeability, oil saturation and other parameters, which provide crucial data support for subsequent oil and gas development and accurate evaluation of reservoir properties.

In the process of drilling, coring, sampling, sample storage and analysis, there are various influencing factors, which lead to the inaccurate experimental data of oil saturation. Therefore, this paper uses the method of drawing the intersection diagram of porosity and water saturation to determine the oil saturation. According to the data of 57 sealed coring samples, the weighted average porosity of Chang 9 reservoir group in the study area is 8.8%, and the corresponding average water saturation is 43.2%. Considering the water loss rate of 3%, the average oil saturation is 53.8% (Figure 7).



**Figure 7.** Relationship between porosity and water saturation in closed coring section of Chang 9 reservoir group.

#### 4.2. Mercury Intrusion Method

The mercury injection experiment is to inject mercury into the rock sample,

measure the amount of mercury injected under different pressures, and draw the mercury injection curve. Through the curve, we can analyze the pore distribution, permeability and fluid saturation of the sample, especially in the calculation of oil saturation. In this paper, the calculation of oil saturation by mercury injection data is mainly based on capillary pressure formula and  $J$  function formula.

$J$  function is a dimensionless function used to describe the relationship between capillary pressure and saturation in petroleum engineering and geology. Its mathematical expression is:

$$J = \frac{P_c}{\gamma n \cos \theta} \sqrt{\frac{K}{\phi}} \quad (2)$$

In Equation (2):  $P_c$  is capillary pressure, MPa;  $\gamma$  for the interfacial tension, mN / m;  $\theta$  contact angle;  $K$  is permeability,  $10^{-3}$  mD;  $\phi$  for porosity, %.

Let  $C = \frac{1}{\gamma \cdot \cos \theta} \sqrt{\frac{K}{\phi}}$ , then the formula can be obtained:

$$P_c = \frac{J}{C} \quad (3)$$

Capillary pressure is an important parameter to describe the pressure difference at the interface between two immiscible fluids in porous media. It is determined by interfacial tension and pore geometry, reflecting the distribution and flow characteristics of fluid in porous media. Its classical formula is:

$$P_c = \frac{2\gamma \cdot \cos \theta}{r} \quad (4)$$

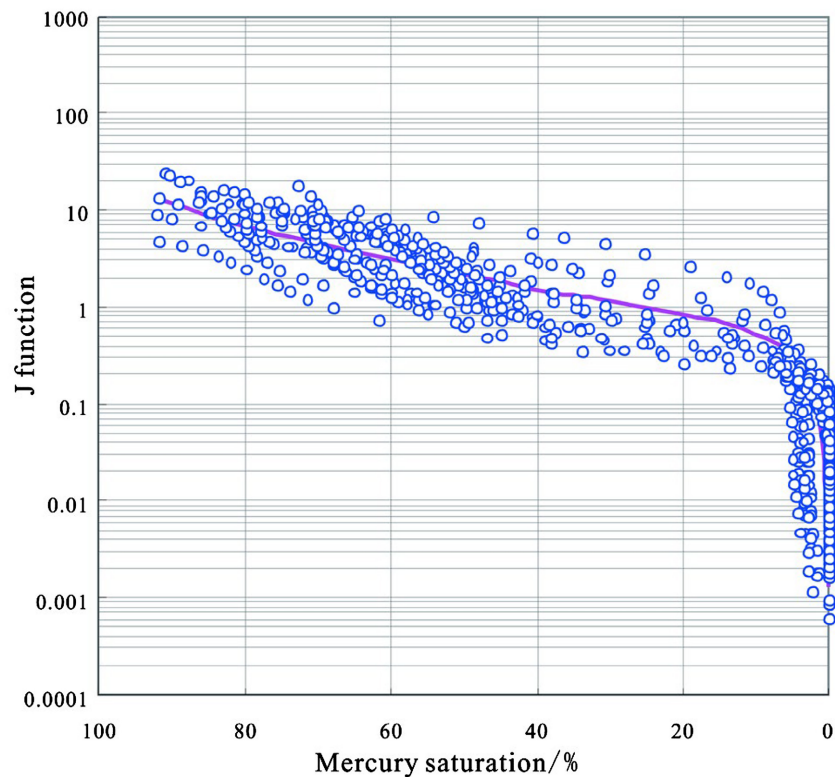
In Equation (4):  $P_c$  is capillary pressure, MPa;  $\gamma$  for the interfacial tension, mN/m;  $\theta$  contact angle;  $r$  is the pore radius,  $\mu\text{m}$ .

For the data of 27 high-pressure mercury injection samples in the study area, the intersection diagram of mercury saturation and  $J$  function is drawn (Figure 8), and the intersection diagram of mercury saturation and average capillary pressure is obtained by formula (2) (Figure 9). According to the intersection diagram of porosity and throat median radius ( $R_{50}$ ) (Figure 10), the lower limit value of porosity is 6.5%, and the corresponding  $R_{50}$  value is 0.041  $\mu\text{m}$ . According to the intersection diagram of the median radius and the displacement pressure (Figure 11), the corresponding  $P_c$  value is 18.09 MPa. Finally, according to the intersection diagram of mercury saturation and average capillary pressure, it is known that when the  $P_c$  value is 18.09 MPa, the corresponding  $S_o$  value on the average capillary pressure curve is 59.5%, which is subtracted by the skin factor of 5%, and the original  $S_o$  is 54.5% (Figure 9).

### 4.3. Phase Infiltration Method

The relative permeability experiment is used to study the flow characteristics of multiphase fluids (such as oil, gas and water) in porous media (such as rock). Through the relative permeability experiment, the relative permeability of different fluid phases under coexistence conditions can be determined, which is an im-

portant reference data in the process of reservoir development.



**Figure 8.** Chang 9 reservoir average  $J$  function curve.

In the process of oilfield development, when the water content is 0%, it indicates that the reservoir is initially pure oil production. As the water content gradually increases, the reservoir gradually changes from the initial pure oil production to oil-water co-production. When the water content reaches 100%, the reservoir will also become pure water production. Therefore, it is considered that when the water content is 10% - 90%, the corresponding water saturation is the water saturation of the same layer of oil and water (Wang et al., 2016b).

Through the relative permeability data of 30 samples in the study area, the relative permeability and water content curves of Chang 9 reservoir group in Zhouchang area were drawn (Figure 12). According to the data of 56 oil test results, the average water content of Chang 9 reservoir group in the study area is 78.6%. Therefore, it is concluded that the oil saturation of Chang 9 reservoir group is 57.6%.

#### 4.4. Logging Interpretation—Archie Formula

Archie formula is a classical method for calculating oil saturation in reservoir engineering. Based on resistivity logging data, oil saturation is indirectly derived by establishing the relationship between rock resistivity and water saturation. When it is assumed that: 1) The rock is pure sandstone and does not contain mud; 2) Formation water is the only conductive medium; 3) The pore structure of rock is uniform. The basic form of Archie formula is:

$$S_w^n = \frac{a \cdot b \cdot R_w}{\phi^m \cdot R_t} \quad (5)$$

In formula (5):  $S_w$  is water saturation (dimensionless); for the formation water resistivity,  $\Omega\text{m}$ ;  $\phi$  is the porosity (dimensionless);  $a$  is the lithology coefficient;  $b$  is the coefficient, which is related to lithology;  $m$  is the cementation index;  $n$  is the saturation index.

According to Archie's formation factor (relative resistivity  $F$ ) formula:

$$F = \frac{a}{\phi^m} \quad (6)$$

Based on the rock electrical analysis data, the cross plot of formation factors and porosity is drawn (**Figure 13**), and the relationship between formation factors and porosity is obtained:

$$F = 0.9513\phi^{-1.7087} \quad (7)$$

It is concluded that the lithology coefficient of the study area is 0.9513, and the  $m$  cementation index is 1.7087.

According to Archie's resistance increase coefficient (I) formula:

$$I = \frac{b}{(1 - S_o)^n} \quad (8)$$

The cross plot of resistivity increase coefficient and water saturation (**Figure 14**) is drawn, and the relationship between resistivity increase coefficient and water saturation is obtained:

$$I = \frac{R_t}{R_0} = 1.015S_w^{-1.6181} \quad (9)$$

It is concluded that the  $b$  coefficient of the study area is 1.015 and the  $n$  saturation index is 1.6181.

According to the rock electrical data, the formation water resistivity of the Chang 9 oil layer group in the study area is 0.16  $\Omega\text{m}$ . Therefore, the logging interpretation model of oil saturation of Chang 9 reservoir group in the study area can be established:

$$S_w = \left( 0.9513 \times 1.015 \times 0.16 / (\phi^{1.7087} \times R_t) \right)^{1/1.6181} \quad (10)$$

It can be calculated that the oil saturation of Chang 9 reservoir group in this area is 54.6%.

## 5. Method Analysis

The sealed coring method is the most accurate method to calculate the oil saturation of the reservoir, which is suitable for complex formations, especially low permeability, fractured or loose formations. However, its accuracy is based on drilling, coring, sampling, and sample storage, until the analysis and testing process, each link will not be disturbed by other factors, followed by closed coring tools and complicated operation, expensive equipment, not suitable for a large number

of sample data, individual Several wells lack representative data.

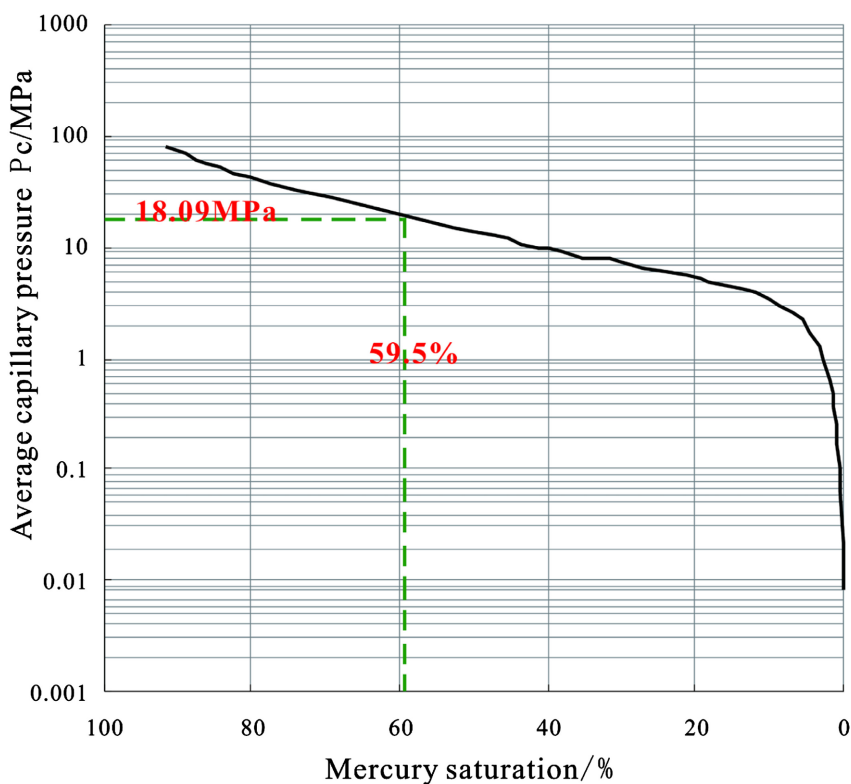


Figure 9. Chang 9 reservoir average capillary pressure curve.

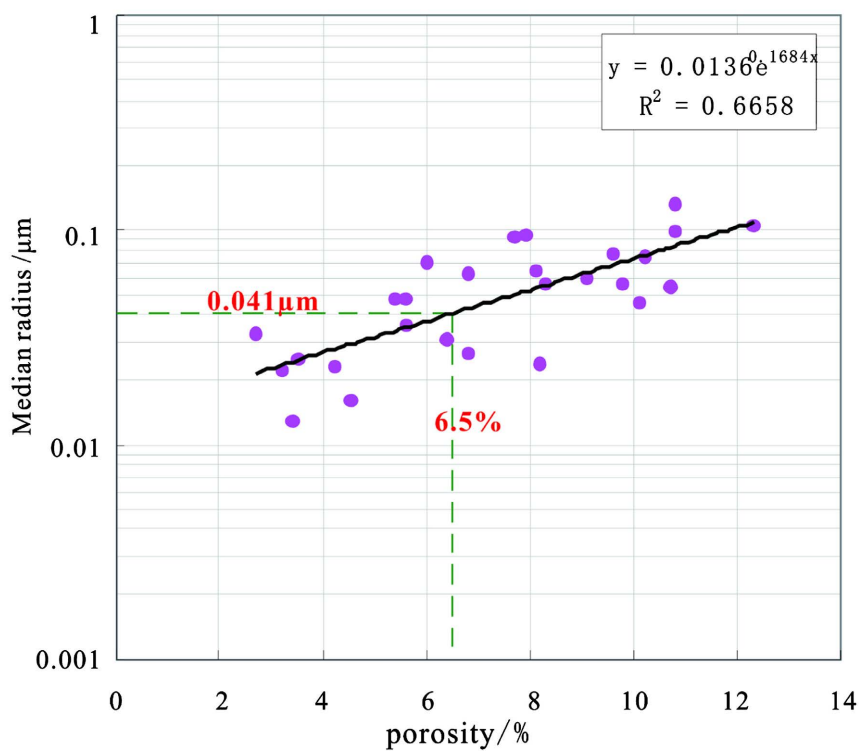


Figure 10. Relationship between median radius and porosity of Chang 9 throat.

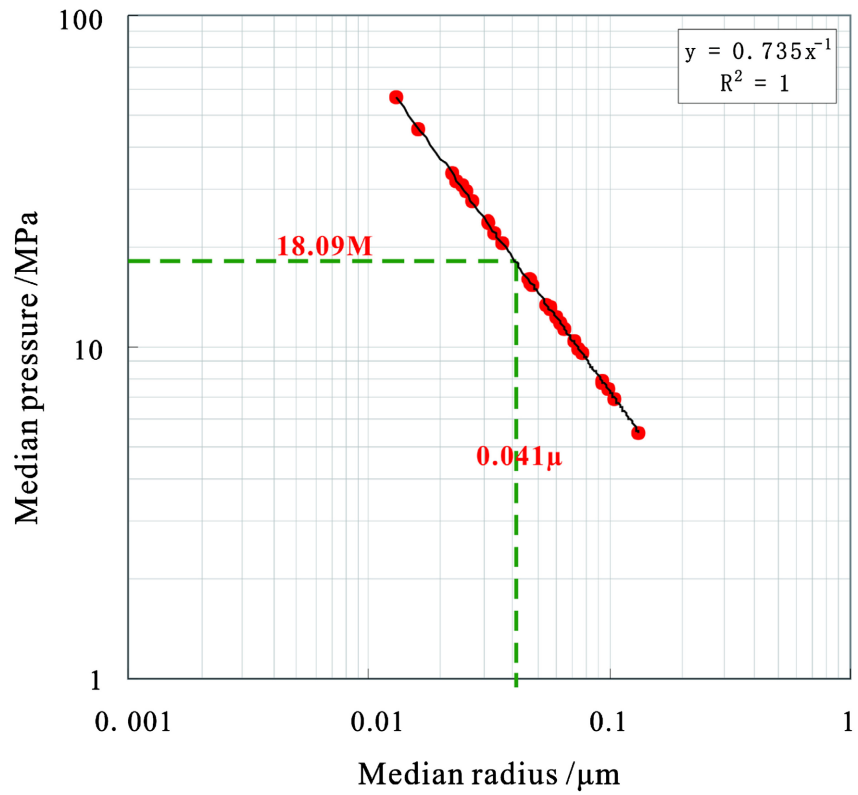


Figure 11. Chang 9 reservoir average capillary pressure curve.

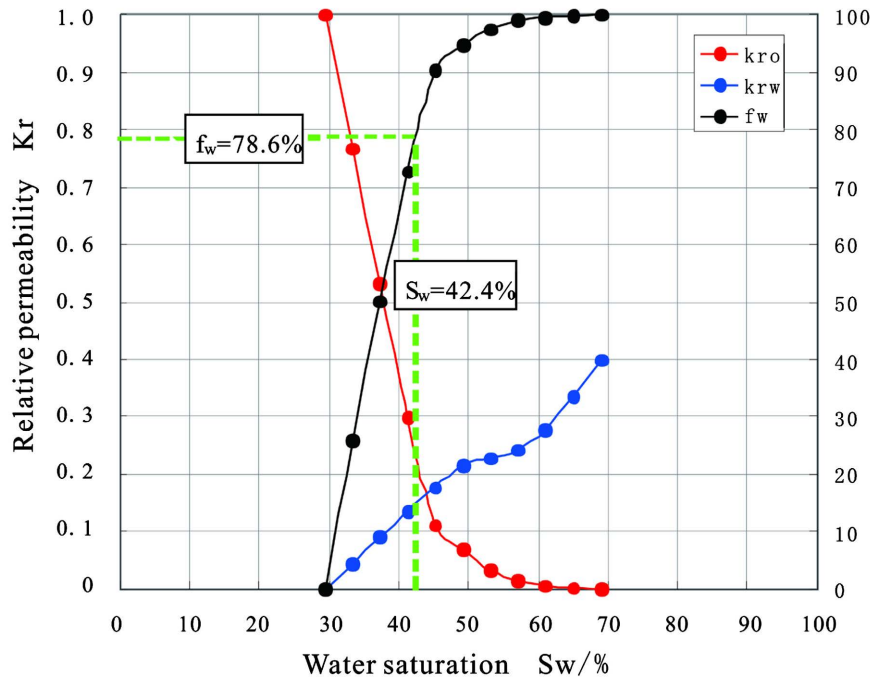


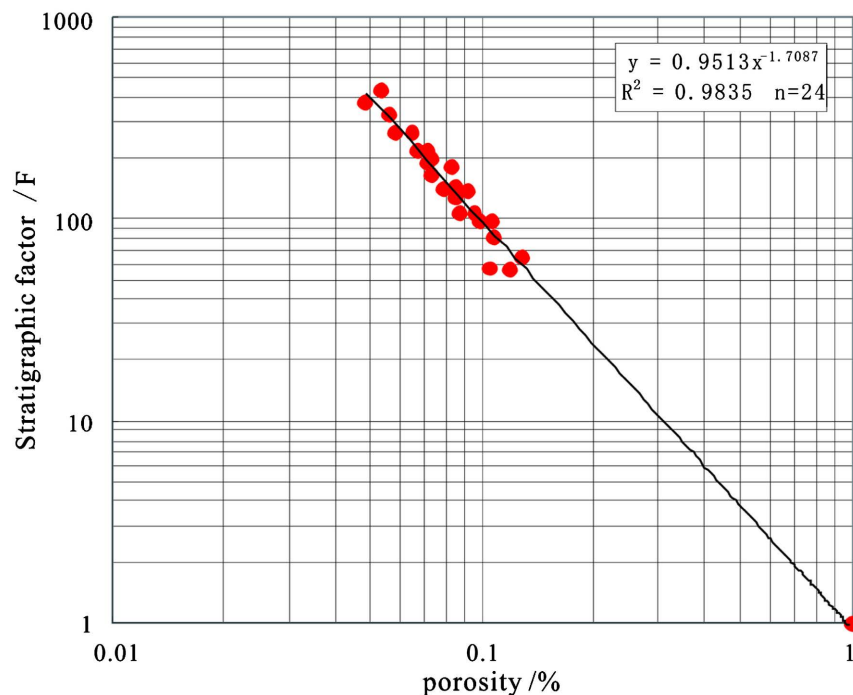
Figure 12. The relative permeability and water cut curve of Chang 9 oil layer group.

The mercury intrusion method can accurately measure the pore size distribution of rock. Compared with other methods, the mercury intrusion method has

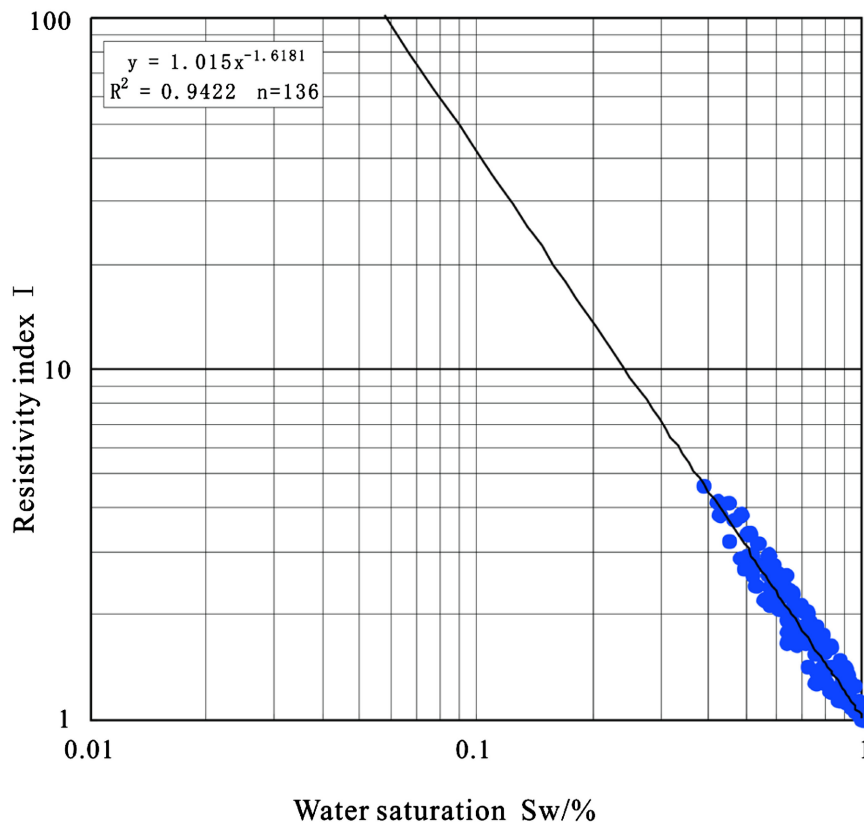
short measurement time and high efficiency. However, after the test, the core sample was contaminated and other experiments could not be carried out; moreover, in the process of high-pressure mercury injection, the pore structure of rock may be destroyed, resulting in inaccurate measurement results; there is also a small size of the experimental sample, which may not reflect the characteristics of the entire reservoir. In addition, the experimental equipment is expensive, mercury has high toxicity, and the cost of waste mercury treatment is high.

The relative permeability method can dynamically reflect the fluid flow characteristics and is suitable for a variety of reservoir types, including conventional and unconventional reservoirs. At the same time, the relative permeability data provided by it can be directly used for reservoir numerical simulation to optimize the development plan. However, its experimental operation is complex, time-consuming, costly, and greatly affected by experimental conditions (such as pressure, temperature, fluid properties, etc.). Moreover, this method cannot directly measure oil saturation, and can only be indirectly calculated by relative permeability curve, with large errors. In addition, the experimental method for strong heterogeneity of the reservoir, the results can not accurately reflect the actual fluid flow.

Logging interpretation method is a very common method to calculate oil saturation based on oilfield logging data. Firstly, logging data acquisition is simple and easy to obtain, and the cost is low. Secondly, the model parameters are few and easy to calculate. It is classical and universal, and it is convenient to calculate the oil saturation of each well in the whole area. Moreover, cementation index and saturation index can indirectly reflect rock porosity and fluid distribution characteristics,



**Figure 13.** Chang 9 formation factors and porosity relationship diagram.



**Figure 14.** chang 9 resistance increase rate and water saturation diagram.

which can guide reservoir evaluation. However, the method depends on the resistivity of formation water and needs to be corrected. At the same time, the influence of wettability is not considered, and it is not applicable to mudstone formation.

Considering that this area is an oil area of Wuqi Oilfield, the distribution area is not large, and the oil layer is relatively concentrated. The logging interpretation method has low cost and strong applicability, especially for small plots, which is simple, fast and accurate. Therefore, this paper uses the logging interpretation method as the final oil saturation calculation method, and the original oil saturation calculation result is 54.6% (Table 3).

**Table 3.** Comparison of oil saturation values in the peripheral long area.

sealed core data method	mercury cutoff penetration method	relative permeability	well logging	Absolute error with logging method	Final value
53.8	54.5	57.6	54.6	0.8 0.1 -3.0	54.6

### 6. Conclusion

1) The sandstone reservoir of Chang 9 oil layer in the peripheral area of Wuqi Oilfield in Ordos Basin is a tight sandstone reservoir with ultra-low porosity and ultra-low permeability. The primary pores dominated by intergranular pores are developed, and the secondary pores dominated by dissolved micropores are de-

veloped.

2) Based on the core, logging, mud logging and oil test data, combined with the experimental data, the original oil saturation of Chang 9 reservoir in the northeast of Wuqi area was calculated by four methods: closed coring method, mercury injection method, relative permeability method and logging interpretation method. The final results show that the oil saturation calculated by the closed coring method is 53.8%, the oil saturation calculated by the mercury intrusion method is 54.5%, the oil saturation calculated by the relative permeability method is 57.6%, and the oil saturation calculated by the logging interpretation method is 54.6%. Considering the advantages and disadvantages of each method, the original oil saturation method conforming to the Chang 9 oil layer group in the local area is determined to be the logging interpretation method, and the original oil saturation in this area is determined to be 54.6%. The determination of its value can provide more basis for the accurate evaluation of tight oil effective reservoir reserves and subsequent reservoir evaluation.

3) With the continuous deepening of tight oil exploration and development work, along with the improvement of oil exploitation and transformation technology, the original oil saturation calculation method is constantly updated, and the calculation results will be more and more accurate. Redefining the original oil saturation is the key and difficult point of long-term research in the field of unconventional reservoirs in the future. The calculation method of the original oil saturation of the tight oil reservoir in Chang 9 reservoir group can provide more reference for other low-permeability unconventional reservoirs

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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