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Research on New Method of Clastic Reservoir Permeability Interpretation

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Abstract

Reservoir permeability is an important parameter in reservoir evaluation and the research on surplus oil distributing regularities. However, it is difficult to calculate it accurately in the process of reservoir interpretation. The ordinary interpretation model uses the rough linear relationship between porosity and permeability within a semi-log coordinate system, resulting in much error. In this paper the permeability calculating formula, including three parameters, porosity, pore-throat radius and pore tortuosity, was deduced from the unity of Poiseuille Capillary Model and Darcy's Law. Based on that, data of core physical properties analysis, mercury injection and well logging were used to construct the empirical relationship between pore tortuosity and pore-throat radius, thus realizing the transformation of permeability calculation from the solo empirical model to the semi-theoretical and semi-empirical model. The calculated results showed that the relative error of the new model was 20.26%, with 22.46 percentage points lower than the error of the traditional empirical model.

Keywords: porosity, pore-throat radius, pore tortuosity, permeability

1. Introduction

Reservoir physical properties are measured by porosity and permeability. Porosity refers to the percentage ratio of pore volume to rock volume in reservoir rocks. Permeability refers to the ability of fluids at certain viscosity to pass through porous rocks. The results of reservoir research show that the error of porosity interpretation is generally smaller while that of permeability is generally larger.

It is commonly known that only when the reservoir permeability is higher than a certain threshold value can the hydrocarbon reservoir be of industrial value. In the research of surplus oil distributing patterns, permeability is the dominant factor on surplus oil distribution (Zeng, 2005; Qiu & Chen, 1996; Li et al., 2004). However, the influence factors of permeability are numerous and some key factors are difficult to calculate in theory. Therefore, the reservoir permeability interpretation model has been in the empirical equation stage for a long time, resulting in large error and low accuracy, becoming a stumbling block in reservoir fine research (Cai, Xiong, & Huang, 1994).

With the purpose to improve the accuracy of permeability interpretation, according to Poiseuille Capillary Model and Darcy's Law, the writer constructed tentatively the empirical formula of pore tortuosity and pore-throat radius on the basis of core property analysis and mercury injection data. Parameter values in the formula were determined through repeated fitting and calculating, realizing the transformation of permeability calculation from the sole empirical formula to semi-theoretical and semi-empirical calculation. The calculated results proved that the new model is constructive in reducing permeability interpretation error.

2. The Main Influence Factors of Permeability

The key influence factors of permeability are clastic particle diameter and mud content. In addition, sorting, psephicity and accumulation mode, clay mineral type and so on are also important influence factors.

(1) Particle diameter: the larger the diameter is, the higher porosity and permeability are.

(2) Mud content: the increasing of mud content will lead to the rapid drop of permeability. According to the research of Moore, an American scholar, with clay mineral content less than 5%, the reservoir is good; with it between 5% and 20%, reservoir properties are bad; with it more than 40%, the reservoir has no permeability.

(3) Clay mineral type: according to lab testing results, with 2% montmorillonite added into quartz sandstone, water sensitivity action can reduce reservoir permeability by 10 times; with 5% montmorillonite added, permeability can be reduced by 30 times; with 15% kaolinite added into the same quartz sandstones, on the condition of low-speed affusion, the rock still has good permeability (He, 2006).

(4) Psephicity and accumulation mode of particles: theoretical calculated results prove that when equant spherical particles are in twin order porosity can be up to 47.64% at maximum, while it is 25.96% with particles in close rhombohedron order. A lot of facts prove that with higher psephicity the reservoir porosity is higher; with more obvious edges, the porosity and permeability are lower.

(5) Sorting of grains: in reservoirs with bad sorting, pores are easy to be filled up with tiny clastic particles; in those with good sorting, porosity and permeability are higher.

3. New Method of Permeability Interpretation

3.1 The Current Situation of Permeability Interpretation

The reservoir permeability cannot be calculated directly by well logging data, therefore, besides the method of core analysis, it is usually calculated by the exponential relation between porosity and permeability, resulting in low accuracy. The following is the calculation formula.

$$\lg(k) = a + b \cdot \phi \tag{1}$$

Concerning the research about clastic reservoir permeability, it is commonly known that accurate interpretation is very difficult because of the complicated influence factors. At present, most scholars think that sedimentary micro-facies determine reservoir physical properties and put forward the concept, Facies-controlling Reservoir, which has been applied widely. Facies-controlling Reservoir can macroscopically control the distribution of physical properties in the reservoirs, but just as qualitative characterization, it can not accurately and quantitatively describe reservoir properties, resulting in severe limitations of its application. Taking distributary channel deposit as an example, the hydrodynamic forces of flowing water are highly various; so are the reservoir physical properties. For the same distributary channel, there are great differences in hydrodynamic forces from the main stream line to the river edges. And so are there in reservoir physical properties.

In order to promote the accuracy of permeability interpretation, by dividing the study areas into different blocks, series of strata, lithologic characters and facies belts, some researchers establish the mathematic models of permeability logging interpretation, which are suitable to the study areas. This method of permeability interpretation based on flow units is advantageous to improve the accuracy of permeability interpretation although it is still on the basis of the conventional model (Ebanks, 1987; Ahr, 1991; Yuan et al., 2005).

3.2 The Theoretical Expression of Permeability

It is an unavoidable fact that the reservoir permeability of the common permeability interpretation model or the model respectively established on flow units is not interpreted upon the analytic expression of permeability and the factors taken into consideration are not comprehensive enough. That is one of the major reasons why the accuracy of permeability interpretation cannot be improved effectively for a long time.

According to Poiseuille Law, porous medium can be reduced to a hank of capillary tubes, which are filled with the fluid with viscosity μ, under differential pressure ΔP, as laminar flow passing through n L-centimeter-long tubes g at the wall radius r. If the ratio between the actual distance and the linear distance of the fluid passing through the rock is τ, the formula of flow calculation is as following.

$$\phi = \frac{n \cdot \pi \cdot r^2 \cdot \tau \cdot L}{A \cdot L} = \frac{n \cdot \pi \cdot r^2 \cdot \tau}{A} \tag{2}$$

$$n \cdot \pi \cdot r^2 = \frac{\phi \cdot A}{\tau} \tag{3}$$

$$Q = \frac{n \cdot \pi \cdot r^4 \cdot \Delta P}{8 \cdot \mu \cdot L \cdot \tau} = \frac{n \cdot \pi \cdot r^2 \cdot r^2 \cdot \Delta P}{8 \cdot \mu \cdot L \cdot \tau} = \frac{\phi \cdot A \cdot r^2 \cdot \Delta P}{8 \cdot \mu \cdot L \cdot \tau^2} \tag{4}$$

According to Darcy's Law, it is known that:

$$Q = K\frac{A \cdot \Delta P}{\mu \cdot L} \tag{5}$$

The flow of the capillary tubes equals the flow of Darcy's Law, therefore, we can get:

$$Q = \frac{\phi \cdot A \cdot r^2 \cdot \Delta P}{8 \cdot \mu \cdot L \cdot \tau^2} = K\frac{A \cdot \Delta P}{\mu \cdot L} \tag{6}$$

After simplifying the above function, we can get:

$$K = \frac{\phi \cdot r^2}{8 \cdot \tau^2} \tag{7}$$

From the above deduced theoretical expression of permeability it can be seen that the ability of a fluid to pass through a rock depends on porosity, pore-throat radius and tortuosity of the rock. Porosity is the key parameter. Permeability is directly proportional to porosity and pore-throat radius square, and inversely proportional to pore tortuosity square (Huang et al., 1994). Tortuosity and pore-throat radius have more effects on permeability than porosity does, therefore, it is inevitable to produce large interpretation error to ignore tortuostiy and pore-throat radius and interpret permeability by the simple semi-log relation between permeability and porosity.

Clastic reservoirs are made up of clastic particles and matrix. Lab tests and oilfield practices prove that reservoir permeability is directly proportional to the size and content of clastic particles, and inversely to matrix content. According to the statistics of core properties analysis data, permeability usually rises as reservoir porosity increases. Through core observations it is found out that generally medium-sized sandstone has good oil-bearing potential while fine sandstone and siltstone have bad potential. Therefore, reservoir permeability goes up as the particle diameter rises. However, for some medium-sized sandstone the oil-bearing potential becomes bad because of high mud content, and even there is no oil in the sandstone reservoir; in the context of low mud content, fine sandstone and siltstone have good potential. The changes of the oil-bearing potential show that reservoir permeability decreases as mud content increases.

Some researchers find out that a few fine-silty sandstone reservoirs have high porosity while their permeability is not high and sometimes even very low (Wang & Cao, 2010; Guo, 2004). This understanding may be mistaken because the deposition of fine clastic particles goes with a large quantity of mud and the acoustic time difference of mud is large, resulting in the interpretation of high porosity. If the mud rectification is done to correct the porosity to the reasonable level, this kind of contradiction may disappear. Then for rocks with little changes of particle sizes porosity is directly proportionate to the particle diameter. The sediment with large differences in grain diameter as well as mélange accumulation is the result of fast deposition, and porosity and permeability is usually very low while the mud content is generally high. Porosity and permeability can be rectified by the methods like mud rectification.

3.3 The Empirical Function of Tortuosity

According to the definition of tortuostiy, with coarser clastic particles and higher porosity as well as shorter distance of fluid particles passing through the rock, tortuosity is smaller; when the mud content is high, filling up into the pores, leading to the complex motion path of the fluid particles passing through the rock, tortuosity becomes large. Tortuosity mainly depends on these two aspects. The basic rule is that tortuosity is directly proportionate to clastic particle diameter and inversely to mud content.

Particle diameter is difficult to calculate by logging data while porosity can be calculated by porosity-logging methods like acoustic time difference. According to the basic theories of Sedimentology, on strong hydrodynamic environments coarse-grain sediment is dominant with large clastic particle diameter and high porosity; on weak hydrodynamic environments fine-grain sediment is dominant with small diameter and low porosity (Hu, 1989; Zhong et al., 2003; Ma, Li, & Liu, 2005; Zhang et al., 2006). Porosity indirectly characterizes the particle diameter, therefore, porosity is used to replace the clastic particle diameter, which is difficult to read from logging information. The relation between particle diameter and tortuosity becomes the relation between porosity and tortuosity.

There are two types of logging information closely related with mud content, self-potential and natural gamma curves. According to the analysis of logging theories, it is reasonable to calculate mud content by natural gamma curve. Mud content is usually calculated by Hilchie Relative Value, and the calculation formula is as following.

$$sh1 = \frac{GR - GR\min}{GR\max - GR\min} \tag{8}$$

$$vsh = \frac{2^{GCUR \cdot sh1} - 1}{2^{GCUR} - 1} \tag{9}$$

According to the research results, the expression of tortuosity cannot be deprived in theory, tortuosity cannot be measured in lab tests and there is no empirical calculation formula of tortuosity. In the process of this research, the writed regarded tentatively porosity and mud content as the major variable parameters of tortosity, on the basis of the above understandings construced the empirical formula of tortuosity and drew tortuosity curve (Figure 1).

$$\tau = a1 + a2 \cdot \phi^{a3} + a4 \cdot (vsh / 50)^{a5} \tag{10}$$

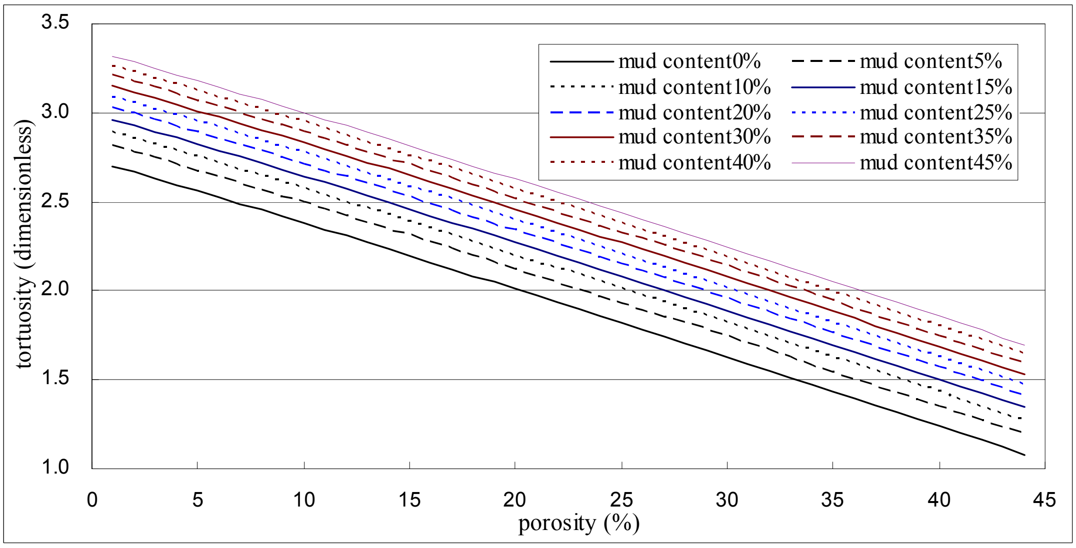

Figure 1. Curve of tortuosity

3.4 The Empirical Function of Pore-throat Radius

Pore-throat radius has similar influence factors to tortuostiy with reverse effects. With bigger particle diameter and higher porosity, pore-throat radius is bigger; with smaller diameter and lower porosity, it is smaller. With more mud it is smaller; with less mud it is bigger.

Pore-throat radius can be calculated by lab capillary pressure data, and yet there is no direct method applying logging information. Porosity was still used to replaced particle radius, and according to the above understanding the empirical function of pore-throat radius was constructed and pore-throat radius curve was drawn (Figure 2).

$$r = \frac{b1 \cdot \phi^{b2}}{(b3 + b4 \cdot (vsh / 50))^{b5}} \tag{11}$$

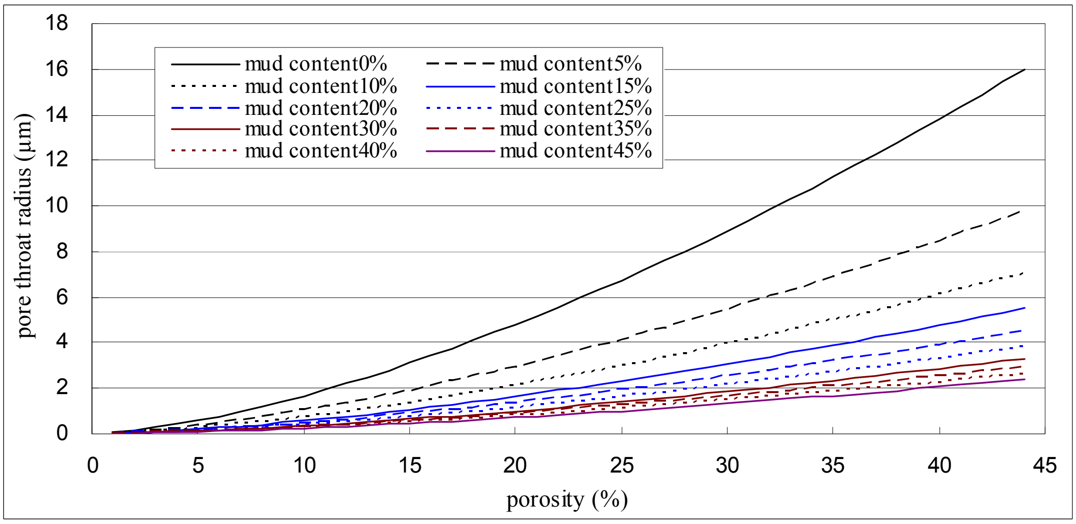

Figure 2. Curve of pore-throat radius

3.5 Model Calculation

The process of calculating permeability is relatively complex. First, acoustic-porosity interpretation model is established to calculate porostiy, and mud content of the corresponding well section is calculated by natural gamma digital logging data. Then applying the data of core property analysis, capillary pressure and acoustic digital logging, based on the theoretical model of permeability, and the construced empirical models of tortuosity and pore-throat radius, parameters in empirical models of tortuosity and pore-throat radius were calculated after many times repeated step-by-step regressions. The calculation of the parameters were on the following conditions: on the condition of lab tests the contributory values of pore-throat radius at different grades to permeability are compatible the calculation results of the empirical model, and the results of average pore-throat radius are compatible with those of capillary pressure tests, and core analysis permeability was consistent with the permeability calculated by the model. Parameters were determined when the relative error of permeability is the smallest.

4. Model Accuracy and Its Application Effects

The data of this research were based on 126 groups of lab analysis data. After core location, invalid data of non-reservoirs and data with large errors were removed, and 94 groups of experimental data were filtered as the basis data for this research.

In order to test the accuracy of this permeability model, the usual semi-log model of permeability and porosity was applied and compared with the results of core analysis (Figure 3), and the relative error of the interpretation permeability was 42.72%. Then, the new model was applied and the relative error was 20.26% (Figure 4 and Figure 5).

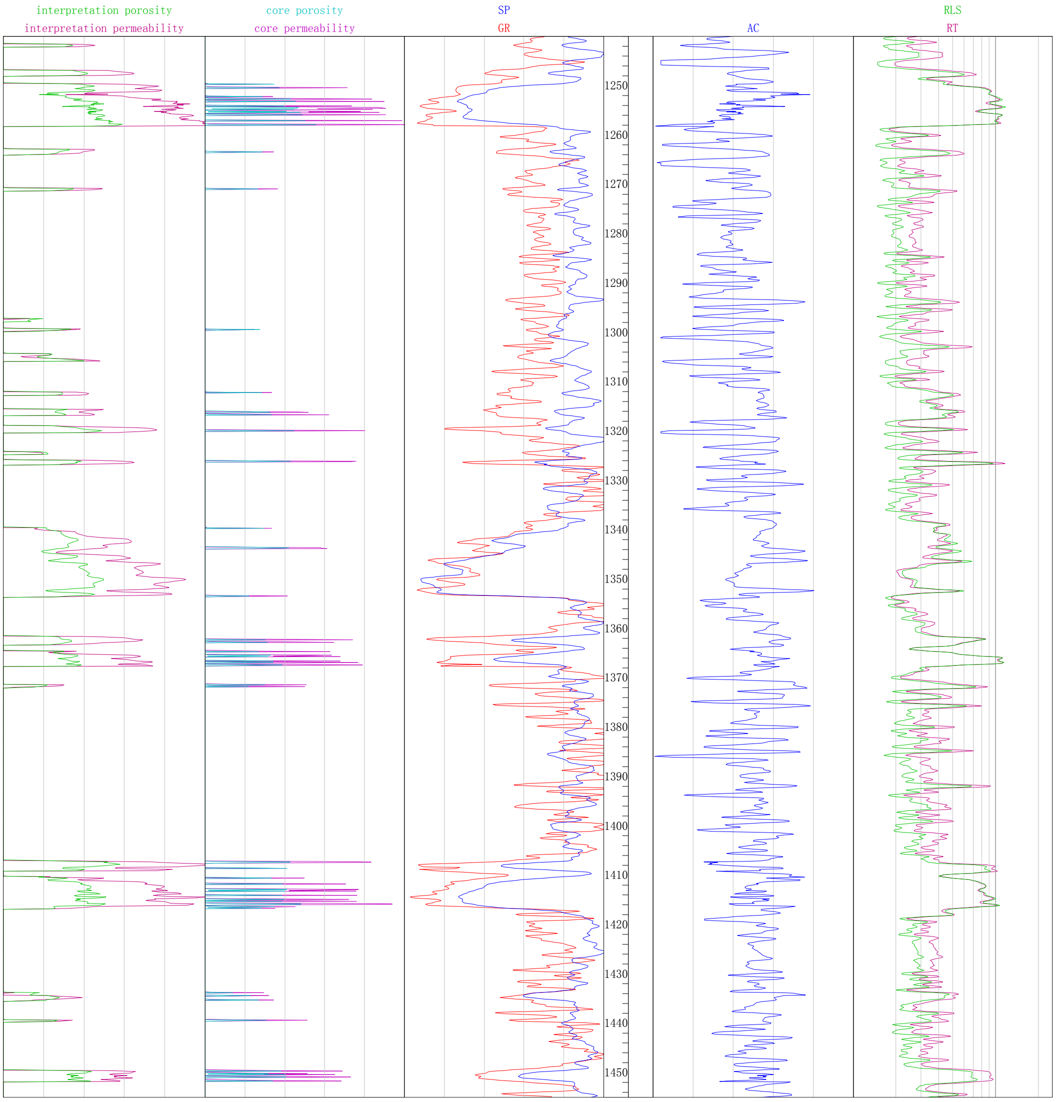

Figure 3. Comparison of interpretation permeability and permeability by core analysis

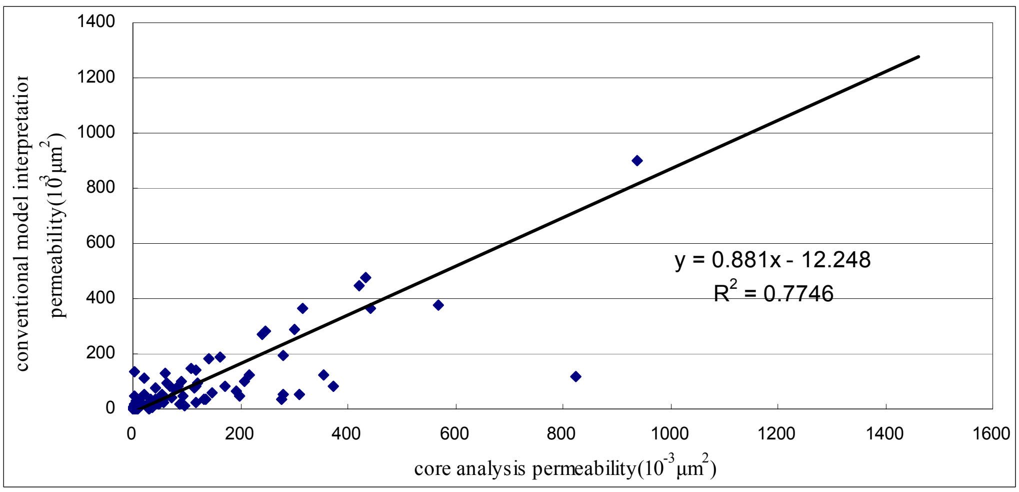

Figure 4. Permeability of conventional model and permeability by core analysis

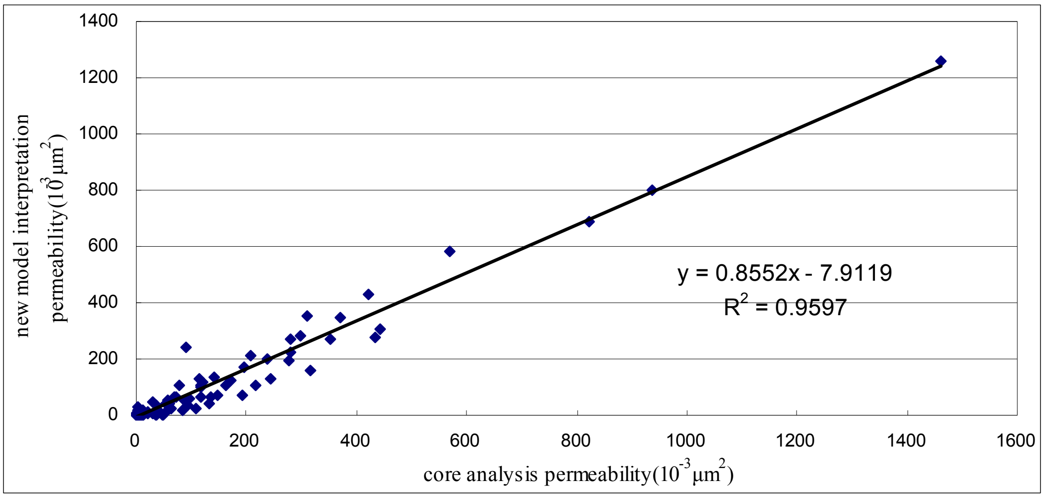

Figure 5. Permeability of new model and permeability by core analysis

By the comparison of the interpretation results of the new and old models, the accuracy of the new model increased by 22.46%.

5. Conclusions and Understanding

(1) The accurate interpretation of permeability is difficult in the research of reservoirs, and the accuracy of the widespreadly applied semi-log interpretation model of porosity and permeability is low and the calculation results have large errors.

(2) There are many influence factors on permeability, for some of which theoretical analytic expressions are hard to deprive. It can be seen from the permeability interpretation model deduced from Darcy's Law and Poiseuille Capillary Model that besides porosity tortuosity and pore-throat radius are important factors in the process of permeability interpretation.

(3) Tortuosity is mainly related to clastic particle diameter and mud content. With bigger particle diameter and higher porosity, pore-throat radius is bigger; with smaller diameter and lower porosity, it is smaller. With more mud it is smaller; with less mud it is bigger.

(4) The main influence factors on pore-throat radius are still clastic particle diameter and mud content. Pore-throat radius increases as particle diameter and porosity goes up, decreases as particle diameter and porosity go down and as mud content increases.

(5) The new permeability interpretation model tentatively constructed in this paper is semi-theoretical and semi-empirical, breaking through the traditional empirical model, providing a new idea to the accurate calculation of permeability.

(6) In the process of matching the core analysis results with logging data, core location and data filtering are very important, and removing some invalid data is favorable for the correct understanding of the objective laws of permeability.

(7) To determine the parameters in the new model of permeability interpretation is relatively complex, and it can be solved with the help of computers.

(8) The application effects prove that the accuracy of the new model is 22.46 percentage points higher than that of the conventional model, which is of great significance to the fine reservoir research.

(9) The new model has been successfully applied to the reservoir research of Dong Zhuang Oilfield and Yang Lou Oilfield with satisfactory application effects.

(10) The new model of permeability interpretation should be constructed upon the geological characteristics of different blocks, and to some extent the accuracy depends on the abundance and the accuracy of the information of the blocks. The application effects still need to be further tested in practice.

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Symbol Notes:

k—permeability, 10-3μm^2	φ—porosity, %	n—amount of capillary tubes
r—radius of capillary tubes, μm	Q—quantity of flow, cm^3	μ—viscosity, mPa.s
ΔP—differential pressure, MPa	A—area, cm^2	L—length, cm
τ—tortuosity, dimensionless	a, b, c, d, e—coefficient	vsh—mud content, %