Analysis of the formation mechanism of upper paleozoic clastic rock reservoir in the southeastern Ordos basin

The formation mechanism of clastic reservoirs in the Upper paleozoic in southeastern Ordos basin is systematically studied by using a large number of rock and mineral analysis and testing data. It is pointed out that the sedimentary environment, petrological characteristics, burial diagenesis, abnormally high fluid pressure and medium environment of salt lake water are the formation mechanisms that control the diagenetic evolution and reservoir property of the reservoirs. And it is put forward that the main reservoir space for the high efficiency reservoirs of sandstone in the upper paleozoic of the Ordos basin includes various types of denudation pores and residual intergranular pores, and that the plastic particle content and particle size in the detrital component of the reservoir are the important mechanisms for the formation of the reservoir.

Keywords: Upper paleozoic,clastic reservoir, formation mechanism, Ordos basin

1. Introduction

The southeastern Ordos basin has very favourable petroleum geological conditions. It isvery close to the Tertiary Red Lion petroleum generative depression and Mangnai petroleum generative depression in the basin, with very abundant petroleum source conditions[1-2]. In the past, the degree of studies on the sedimentary facies, provenance and gas reservoir characteristics of a sandstone reservoir in center of the northern part of the upper paleozoic in the Ordos basin was relatively high[3-4], while the degree of studies on the southeastern part of the basin was relatively low[5]. In the existing studies, the sedimentary characteristics, petrological characteristics, lithological characteristics, lithological characteristics and other aspects of the Benxi formation, Shanxi formation and Xiashihezi formation in the segment 8 (referred to as "Block 8" for short)[6-7]of the study area and its adjacent areas have been explored to a certain extent by previous scholars[8]. In general, the reservoir characteristics of mainly a certain layer of the upper paleozoic in the southeastern part were analyzed in previous studies, but there were relatively few studies on the relationship between different diagenesis types and the reservoir properties[9-10].

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In this paper, the well log of more than 60 drilling wells, cutting logging and drill core (with the drill core length of about 5000m) data as well as a large number of rock casting thin slices, scanning electron microscopy, bore, permeability and other rock and mineral testing data were used to study the characteristics of the sandstone reservoir as the main hydrocarbon bearing strata in this area. The formation mechanism of the sandstone reservoirs has been analyzed and studied systematically for the first time. And it is pointed out that the sedimentary environment, petrological characteristics, burial diagenesis history, formation fluid pressure and the aquifer environment of the salt lake are the main formation mechanisms of the reservoir properties. It will be conducive to further understanding and predicting the law of the regional development of the sandstone reservoirs in the southeastern Ordos basin.

2. Formation mechanism of the reservoir

2.1 Sedimentary Environment is the basis for the determination of the nature of the reservoir

The relatively great differences in the lithologic characteristics of the clastic reservoir formed in different sedimentary environments endow the reservoirs significant differences as well.The southeastern part of the Ordos basin (E_3^1) is mainly composed of the delta front and the lakeshore sediments, the development lakeshore sand flat, the underwater distributary channel of the delta front, the estuarine dam and other reservoir bodies. The physical properties of the typical sedimentary sand bodies in the area are set out in Table 1. From Table 1, it can be seen that after the effect of agglutinate is ruled out, the microfacies sandstone in the underwater distributary channel have the best reservoir properties due to the fact that the particle size is relatively coarse grained, with the average permeability up to 290@10-3Lm^2. The physical properties of the sandstone microfacies are closely related to the rock particle size. The reservoir in the fine sand grade has the best physical properties, and the average permeability is more than 100@10-3Lm^2. The porosity of the reservoir in the silt gradeunder the condition of the depth of burial smaller than about 3800m can still remain between 12% and 16%, but its permeability is less than 10@10-3Lm^2.

TABLE 1. COMPARISON OF THE RESERVOIR PHYSICAL PROPERTIES OF DIFFERENT SEDIMENTARY MICROFACIES IN THE SOUTHEASTERN ORDOS BASIN

Well Number	Depth/m	Microfacies	Lithology	Porosity/%	Permeability/ (@10-3Lm^2)	Content of agglutinate
Yue No. 110	3417~3465	Sand flat	Fine sandstone	16.5	213.15	9.5
Yue No. 110	3354~3417	Sand flat	Fine sandstone	9.1	2.46	20
Yue No. 24	3612~3686	Sand flat	Fine sandstone	17.8	143.6	9.2
Yue No. 24	3612~3686	Sand flat	Siltstone	16	6.9	4.8
Yue No. 111	3324~3393	Sand flat	Fine sandstone	18.3	116.3	<10
Yue No. 111	3324~3393	Sand flat	Siltstone Siltstone	15.3	8.3	310
Yue No. 12	1787~1817	Underwater distributary channel	Fine/medium/coarse sand	16.4	290.4	11
Hone No. 20	3274~3305	Underwater distributary channel	Silt/medium and coarse sand	3.01	0.2	18.8

The southeastern part of the Ordos basin (N_1 and N_2^1) consists mainly of the deltaic plain, the delta front and the lakeshore sedimentation, the development delta plain distributary channel, the delta front distributary channel, the estuarine dam, the lakeshore sand flat and other reservoir bodies. In Table 2, the physical properties of the reservoir with N_1-N_2^1 typical sedimentary microfacies sand body in the area are set out. Similarly, it can be seen that after the effect of the agglutinate is ruled out, the physical properties of the reservoirs at the plain distributary channel and the underwater distributary channel microfacies are the best, with the highest average permeability up to 732@10-3Lm^2. The physical properties of the reservoir of the sandstone microfacies are closely related to the rock particle size. The properties of the reservoir of the fine/medium sandstone are relatively good with the average permeability of 340@10-3Lm^2. The permeability of the reservoir of the fine sandstone is generally less than 100@10-3Lm^2; while the porosity of the reservoir in the silt sandstone grade is 12~18%, with the permeability less than 10@10-3Lm^2.The lithology of the sandstone reservoir in the estuary dam microfacies is dominated by siltstone and fine sandstone, and the physical properties of the reservoir are similar to those of the sand flat microfacies.

2.2 Petrology Characteristic is an Important Formation Mechanism of Reservoir Properties

The tertiary reservoir sandstones in southeastern part of the Ordos basin are mainly composed of braided river delta and lakeshore depositional system, partly alluvial fan sediments. The composition of the sandstone is relatively low in maturity and rich in volcanic rocks, metamorphic rocks, terrestrial carbonates and various other kinds of rock fragments, with the content up to 40% to 60%. Due to the fact that the compressive properties of the plastic composition of the debris component is relatively weak, these plastic particles are prone to plastic deformation during the burial diagenesis, which, therefore, is not conducive to the preservation of the

TABLE 2. COMPARISON OF RESERVOIR PHYSICAL PROPERTIES OF DIFFERENT SEDIMENTARY MICROFACIES IN THE SOUTHEAST ORDOS BASIN

Well Number	Depth/m	Microfacies	Lithology	Porosity/%	Permeability/ (@10-3Lm^2)	Content of agglutinate
Yuezhong No. 625	1761~1766	Distributary channel	Medium coarse gravel rock	19.4	732.3	<10
Yue No. 54	1667~1756	Distributary channel	Medium coarse gravel rock	17.8	518.9	/
Wu No. 5	1445~1600	Sand flat	Siltstone	11.46	1.56	/
Yue No. 634	1753~1856	Sand flat	Siltstone	15.9	6.2	11
Yue No. 62	1902~1937	Distributary channel	Medium coarse gravel rock	20	133.2	/
Hua No. 5242	896~911	Underwater distributary channel	Fine/medium/coarse sand	20.6	251.3	5.0
Hua No. 5242	532~541	Underwater distributary channel	Fine/medium/coarse sand	20.5	252	7.5
Huanan No. 322	657.3~659.5	Sand flat	Silt/fine sand	19.3	35.5	<10
Huanan No. 322	685.4~687.1	Sand flat	Fine/medium sand	21.5	340.64	/
Huanan No. 322	674.6~677.0	Underwater distributary channel	Fine/medium/coarse sand	18.8	616.2	/

primary pores in the reservoirs. In order to illustrate the effect of the plastic granular components of the reservoir on the nature of the reservoir, the correlation analysis of the plastic particle composition component and the reservoir properties is carried out on the silt fine sandstone and fine sandstone reservoirs in the southeastern part of the Ordos basin with the buried depth of 3300 ~ 3500m and the interstitial content of 6% ~ 10%. The plastic particle composition referred to herein is composed of the volcanic rocks, the metamorphic rocks, the terrestrial carbonate rocks and other debris particles. From the relationship between the plastic particle content and the porosity and permeability of the sandstone in the reservoir, it can be seen that with the increase in the plastic particle content in the reservoir, both the porosity and the permeability of the reservoir are decreased significantly. In particular, the decrease in the permeability is more significant (Fig. 1). When the plastic particle content of the reservoir is increased from 50% to 55%, the porosity of the reservoir is decreased by about 2.0% and the permeability is decreased by about 70@10-3Lm^2.

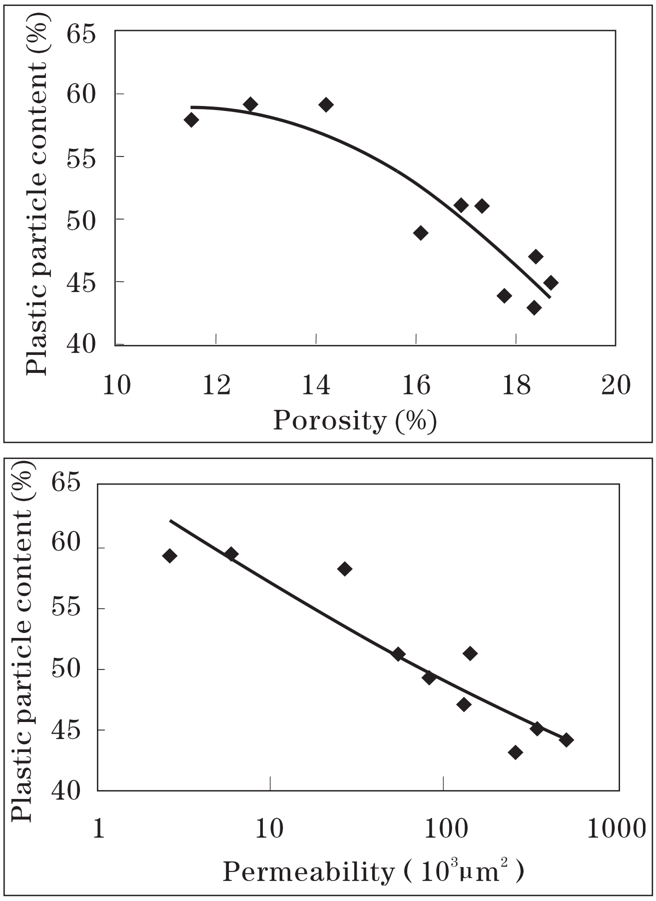

Fig. 1: Quantitative relationship between the content of plastic particle in the reservoir and the porosity and permeability

The effect of particle size of the reservoir on the reservoir properties is mainly reflected in two aspects. First of all, the finer is the particle size, higher is the debris content in the detrital components; higher is the content of plastic debris, in particular, the shallower are metamorphic rocks and terrestrial carbonates. Therefore, the fine-graded reservoirs are more likely to be compacted during the burial diagenesis process, resulting in poor physical properties of the reservoir. At the same time, the smaller is the particle size of the reservoir, the lower is the compressive strength; secondly, under the same compaction conditions, the pores and throats of the coarse-grained reservoirs tend to be greater than those of the fine-grained reservoirs. Therefore, the properties of the coarse-grained reservoirs (in particular, the permeability) tend to be significantly better than those of the fine-grained reservoirs. The statistical results show that under the condition that the burial depth, the interstitial content and the dissolution rate are basically similar, the average porosity of the siltstone reservoir is 13.45%, and the average permeability is 12@10-3Lm^2. The average porosity of the fine sandstone is 14.4%, and the average permeability is 39.9@10-3Lm^2. The average porosity of the fine sandstone is 17.7%, and the average permeability is 186.5@10-3Lm^2. The average porosity of the medium-fine sandstone reservoir is 17.8%, and the average permeability is up to 492.5@10-3Lm^2. From the correlation analysis of the porosity and the permeability of different grain-grade reservoirs, it can be seen that there is good positive correlation between the particle size of the reservoir and the porosity and permeability. On an average, for each grain grade that particle size of the reservoir is increased, the porosity will be increased by 3% ~ 4% or so, and permeability can be increased by 150@10-3~300@10-3Lm^2.

2.3 Particle Size Analysis Method for the Clastic Reservoir of the Upper Paleozoic

In the sedimentary petrology, the method of determining the content of different coarse or fine particles in the sediments or rocks are referred to as the particle size analysis. In the studies of petroleum geology, especially in the research of the reservoir sedimentary facies, the method of particle size analysis also has a very wide range of applications. In the early stage, the method for the processing of the particle size data was relatively simple. And only the moment method or graphical method was used to obtain some particle size parameters, such as the average particle size, the sorting coefficient, the skewness, the sharpness and so on. Later on, it was found that the cumulative probability curves of the particle sizes could be described by using the mixture normal distribution. In this way, it was possible to distinguish the roles of rocks with different particle sizes in the process of sedimentation, so as to better explain the sedimentary formation process.

The particle size distribution of the sediment can be described by mixed normal distribution function as the following:

$$F(x) = \sum_{i=1}^{n} c_i \, \phi \left(\frac{x - \mu_i}{\sigma_i} \right) \tag{1}$$

In the equation: x stands for the value of the small particle size; F(x) stands for the parent distribution function; n stands for the number of sub-body; c_i stands for the coefficient of proportionality of the sub-body; μ_i and σ_i stand for the parameters of the sub-body (mean and variance); Φ(z) stands for the normal probability integral

$$\Phi(\mathrm{z}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{z}} e^{-y^2/2}\, dy \tag{2}$$

The sub-body parameters have relatively clear physical meanings. And the mean μ_i is equivalent to the average particle size. The variance σ_i is equivalent to the sorting coefficient. And the coefficient of proportionality c_i quantitatively reflects the roles played by the various sub-bodies in the handling process. Their combinations reflect the coexistence and mutual restraint relationship of the sub-bodies, all of which indirectly reflect the nature of the handling process and the corresponding combination. For a given rock sample, it is necessary to determine the number n of sub-bodies in the particle size distribution function, the parameters μi and σi of each sub-body, as well as the coefficient of proportionality c_i of the sub-body in accordance with the experimental data of the particle size analysis, in which c_i meets the following conditions:

$$\sum_{i=1}^{n} c_i = 1, 0 \le c_i \le 1 \tag{3}$$

It is assumed that the diameter of the sieve diameter (mm), that is, the particle size arranged in a descending order is d_j, which is converted into the particle size value as the following:

$$x_j = -\log_2 d_j \tag{4}$$

Then the definition is supplemented as the following:

$$\begin{aligned} d_0 &= +\infty, x_0 = -\infty \\ d_{m+1} &= -\infty, d_{m+1} = +\infty \end{aligned} \tag{5}$$

The particle size or particle size interval is defined as the following:

$$D_j = \left\langle \begin{matrix} \{d | d_j \le d < d_{j-1}\} \\ \{x | x_{j-1} < x \le x_j\} \end{matrix} \right., j = 1, \ldots, m+1 \tag{6}$$

When the particle size analysis experiment is carried out, the mass content data p_j in the particle size interval D_j is measured, which meets the following:

$$0 \le p_j \le 1, \sum_{j=1}^{m+1} p_j = 1 \tag{7}$$

The particle size and the cumulative content are obtained as the following:

$$P_j = \sum_{i=1}^{J} p_i \,, j = 1, \ldots, m \tag{8}$$

In the equation: P_j stands for the cumulative content, which is a fraction.

3. Experiment and result analysis

The diagenetic authigenic minerals (mainly carbonates, anhydrite and zeolite) in the clastic reservoirs of the upper paleozoic in the southeast Ordos basin are relatively developed and very well developed in some areas, which leads to significant reduction in the porosity of the reservoirs. Figs. 2, 6, 7 and 8 show the correlation diagrams of the agglutinate content of the reservoir in Shaxi area, which have reflected the effect of the diagenetic cementation on the properties of the reservoir. That is to say, as the content of the agglutinate in the reservoir is increased, both the porosity and the permeability are decreased significantly. In accordance with the statistics on the identification of rock casting thin slices, the porosity reduced due to the cementation effect is between 6.5% ~ 20% in this area and up to 25% ~ 35% in some areas.

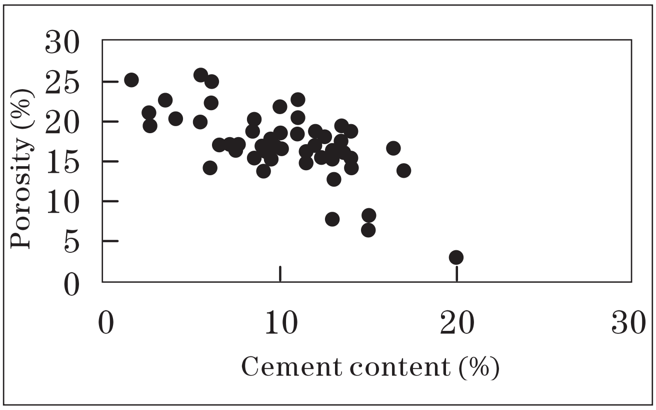

Fig. 2: Correlation diagram of the reservoir and the porosity in southeastern Ordos basin

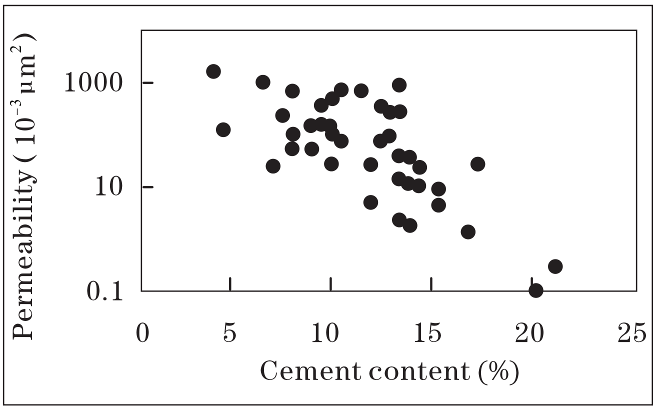

Fig. 3: Correlation diagram of the reservoir and the permeabilityin the southeastern Ordos basin

In order to verify the validity of the particle size analysis method, the samples of the reservoir in the southeast Ordos basin are taken for analysis. The experimental data of the particle size of the sample is shown in Table 3.

Table 3. Particle size experimental data

Particle size / mm	Particle size Φ value	Mass content, %	Cumulative content, %
2.00	-1.00	0.00	0.00
1.00	0.00	0.45	0.45
0.50	1.00	15.90	16.35
0.10	3.32	19.85	78.30
0.05	4.32	6.20	84.50
0.01	6.64	5.75	90.25
0.00098	9.99	9.75	100.00

Among them, the particle size and the mass content are measured values, while the small particle size value and the cumulative content are calculated values. The particle size analysis method is used to determine the particle size separation parameter, the mean value of the sub-body obtained, the variance and the coefficient of proportionality are shown in Tables 4 and 5. The comparison of the cumulative percentage content fitting data is shown in Table 6. The comparison of the percentage content calculation curve and the measured value is shown in Figs. 4 and 5.

Table 4. Sub-body parameters of the particle size distribution (2 sub-bodies)

Sub-body	Coefficient of proportionality	Mean	Variance
1	0.744	1.560	0.713
2	0.256	5.427	2.766

Table 5. Sub-body parameters of the particle size distribution (2 sub-bodies)

Sub-body	Mean	Variance
1	1.571	0.679
2	5.315	2.838
3	1.656	11.82

When the parent are assumed to be a mixture of three normal sub-bodies, the coefficient of proportionality of the third sub-body obtained is almost negligible when it is compared to the other two sub-bodies. From the data in Tables 4 and 5, it can be seen that the coefficient of proportionality, the mean and the variance of the first two sub-bodies are also very close. From the fitting value shown in Table 6 and the error analysis of the measured values, the absolute error and the relative error of the two are basically close. Therefore, it can be considered that the parent is composed of two sub-bodies.

In order to compare the effects of the different ways of defining the objective function on the fitting result, the Euclidean norm is further used to define a fitting objective function as the following:

$$M(x) = \sqrt{\sum_{j=1}^{m} \left| F\left(x_j, x\right) - P_j \right|^2} \tag{9}$$

It can be seen from Table 7 that, the parameter data of the sub-bodies obtained by using the fitting function defined by different norms are relatively close. However, from Table 6, it can be seen that except for the measured points with the low granularity, the maximum absolute error by using the uniform norm is slightly smaller than that by using the Euclidean norm to define the fitting objective function. The closeness of the sixth measured point (with the particle size of 4.32) in Figs. 5 and 6 with the fitting curve are compared, which also shows that the fitting result of the uniform norm is slightly better.

Table 7. Comparison table of sub-body parameters obtained from different norms

Sub-body	Coefficient of proportionality	Mean	Variance	Norm
1	0.744	1.560	0.713	Uniform
	0.755	1.549	0.668	Euclidean
2	0.256	5.427	2.766	Uniform
	0.245	5.684	2.534	Euclidean

Table 6. Comparison table of the cumulative percentage content fitting data

Particle size	Measured value	2 sub-bodies (L0 norm)			3 sub-bodies			2 sub-bodies (L2 norm)		
		Calculated value	Absolute error	Relative error, %	Calculated value	Absolute error	Relative error, %	Calculated value	Absolute error	Relative error, %
-1.0	0.0000	0.0031	0.0031		0.0035	0.0035		0.0011	0.0011	
0.00	0.0045	0.0168	0.0123	273.14	0.0157	0.0112	248.70	0.0107	0.0062	138.44
1.00	0.1635	0.1715	0.0080	4.88	0.1644	0.0009	0.52	0.1629	0.0006	-0.34
2.00	0.5845	0.5719	-0.0126	-2.15	0.5741	-0.0104	-1.78	0.5840	-0.0005	-0.08
3.32	0.7830	0.7959	0.0129	1.65	0.7961	0.0131	1.67	0.7947	0.0117	1.50
4.32	0.8450	0.8321	-0.0129	-1.51	0.8319	-0.0131	-1.55	0.8271	-0.0179	-1.18
6.64	0.9025	0.9154	0.0129	1.43	0.9156	0.0131	1.45	0.9135	0.0110	1.22
9.99	1.0000	0.9871	-0.0129	-1.29	0.9869	-0.0131	-1.31	0.9891	-0.0110	-1.09

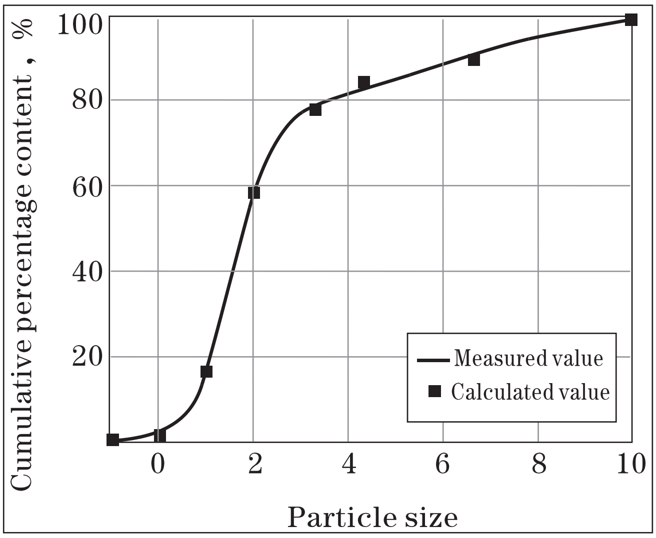

Fig. 4: Cumulative percentage contentcurve (3 sub-bodies)

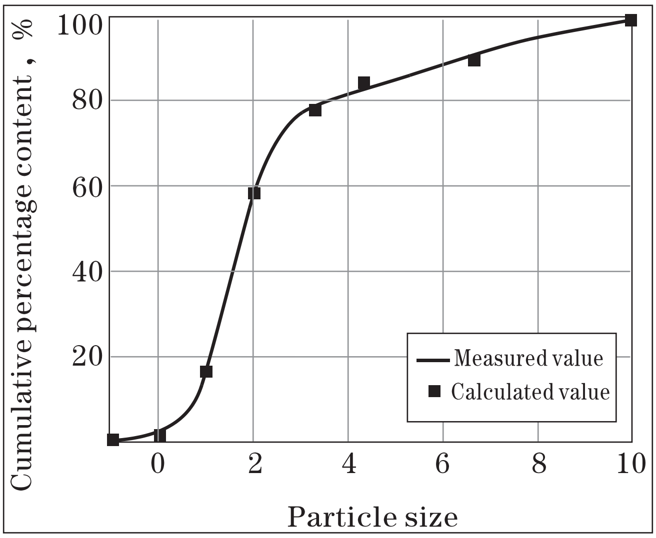

Fig. 5: Cumulative percentage content curve (2 sub-bodies/uniform norm)

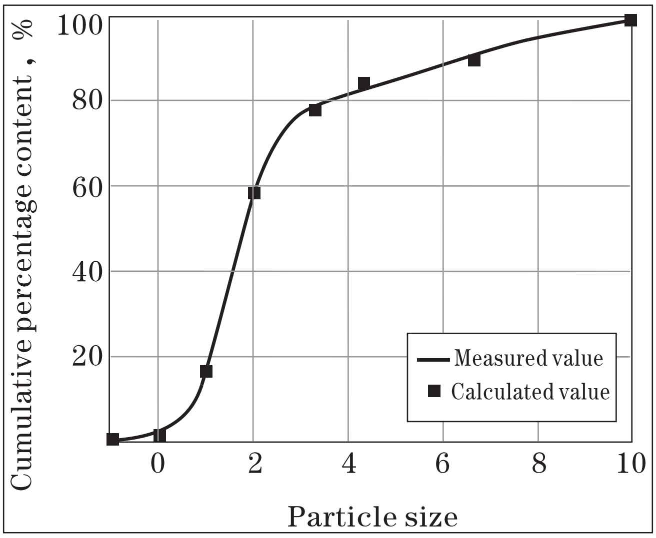

Fig. 6: Cumulative percentage content curve (2 sub-bodies/Euclidean norm)

4. Conclusions

Sedimentary environment is the basic formation mechanism of reservoir properties. And the reservoir properties of the sub-aqueous distributary channel microfacies in the delta front are the best, followed by the fine sand grade reservoirs in the sand flat microfacies. Petrology characteristics are the important formation mechanisms of the reservoir properties, which are mainly reflected in the composition and the particle size of the debris. The plastic composition in the detrital component of the reservoir is relatively weak in the compressive strength and is prone to plastic deformation during the burial diagenesis, which is not conducive to the preservation of the intergranular pores; smaller the particle size of the reservoir is, the higher is the plastic debris content, and lower is the compressive resistance, hence stronger is the compaction of the reservoir. The lithology of the reservoir is affected by the content of the plastic debris in the reservoir which is shown by two aspects, that is, the changes with that of the particle size, as well as the different compressive properties of the reservoirs with different granularities and so on.

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