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ORIGINAL PAPER-EXPLORATION GEOLOGY

Lower limit of effective reservoir physical properties and controlling factors of medium-deep clastic reservoirs: a case study of the Dawangzhuang area in Raoyang sag, Bohai Bay Basin

Chenyu Zhai[1] · Chuanbing Lv[2] · Renan Gao[2] · Fengqun Li[3] · Jun Xie[1] · Shanshan Yu[3] · Zhimin Zhang[3] · Yingshun Mou[3] · Hongmei Wang[2]

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Abstract
With the continuous improvement of oil and gas exploration in the middle and shallow layers, the deep Paleogene in Raoyang sag has become an important exploration field of "increasing reserves and production" in North China. The recognition and control factors of deep effective reservoirs are unclear, which restricts the recognition effect of oil and gas exploration. The key to identify effective reservoirs is to determine the lower limit standard of reservoir physical properties. The single method for calculating the lower limit of physical properties has limitations. The lower limit of the effective reservoir physical properties of the Shahejie Formation in the Dawangzhuang area was obtained by comprehensively using physical property, well logging and oil test data. The data were analysed by oil testing method, metre oil production index test method and frequency curve intersection method. On this basis, combined with the cast thin-section observations, scanning electron microscopy and other test results, the comprehensive control of effective reservoir development of the Shahejie Formation in the Dawangzhuang area of the Raoyang sag was studied from various factors, such as formation pressure, sand body thickness and diagenesis. The results show that the lower limit of porosity was 9.73, 9.44 and 8.85% at depths of Es1, Es2 and Es3, respectively. The lower limit of permeability was 1.21×10^{-3}, 1.18×10^{-3} and 0.59×10^{-3} μm^2, respectively. Effective reservoirs are easier to form in areas with formation pressure coefficient greater than 1.2. Formation overpressure inhibits compaction and promotes dissolution. The proportion of effective reservoirs of sand bodies with thicknesses greater than 2 m can reach more than 75%. The influence of diagenesis on the reservoir is mainly manifested in compaction and cementation making the reservoir compact. The porosity reduction rate caused by compaction can reach 20–75%, while dissolution makes the reservoir form secondary pores. The average pore throat radius of secondary pores can reach 4 ~ 6.3 μm. This study makes use of the applicability of different methods, which is more instructive for predicting the effective reservoir of the Shahejie Formation in the study area. In addition, the research results provide a reference for the development mechanism of medium-deep clastic reservoirs.

Keywords Dawangzhuang · Effective reservoir · Control factors · Diagenesis

List of symbols

h	Thickness (m)
I	Oil production index per metre (t/(MPa d m))
Pe	Formation pressure (MPa)
Pw	Bottom hole flow pressure (MPa)
Q_0	Oil production (t/d)

Abbreviation

AHP	Analytic hierarchy process

✉ Jun Xie
tsingqi@foxmail.com

1 College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao, Shandong, China

2 North China Oilfield Company of PetroChina, Renqiu, Hebei, China

3 The Third Oil Production Plant of North China Oilfield Company of PetroChina, Hejian, Hebei, China

Introduction

In recent years, with the continuous breakthroughs in oil and gas exploration and development and the continuous innovation of exploration technology and methods, research on medium-deep reservoirs has gradually become the focus of oil and gas exploration. The microstructure, diagenesis characteristics, lower limit of effective physical properties and effective reservoir control factors of deep tight reservoirs have become the focus of oil and gas exploration research (Lu et al. 2021). An effective reservoir refers to a reservoir that can store and percolate hydrocarbon fluids and can produce oil and gas with industrial value under the conditions of existing technology. The lower limit of the physical properties of an effective reservoir refers to the lowest physical properties of the effective reservoir. It is usually measured by a certain value of porosity and permeability (Worthington and Cosentino 2005). It is a factor that must be considered in reservoir evaluation and reserve calculation, which directly determines the development decision of the oilfield (Zhang et al. 2014; Worthington 2008; Xiao et al. 2021). Predecessors have made a great deal of understanding of the determination and control mechanism of reservoir lower limits in different areas and under different geological conditions.

Since the birth of petroleum exploration and development, many scholars and experts have carried out research on the determination method of the lower limit of effective reservoir physical properties. According to the data sources, the more mature methods are divided into static methods and dynamic methods (Xiao et al. 2004; Liu et al. 2018). The existing methods for determining the lower limit of effective reservoir physical properties generally use core test and analysis, logging and oil test and production test data and determine the lower limit of physical properties by means of statistical analysis and construction of a relationship diagram (Li et al. 2012; Cong et al. 2014; Cui et al. 2017; Monsees et al. 2020). In view of the phenomenon that the lower storage limit of clastic rock reservoirs decreases with increasing burial depth, Wang and Cao (2010) proposed the method of qualitative classification evaluation by using the physical property difference (the difference between the physical property value of the reservoir at a certain depth and the lower physical property value of the corresponding depth) as the reservoir evaluation parameter. However, due to the inaccurate calculation of the lower limit of physical properties due to a single method, there are subjective factors in the qualitative evaluation, which makes the evaluation results different from the actual geological situation. Bao et al. (2005) proposed using the average daily liquid production as a quantitative evaluation standard for reservoir classification evaluation. However, due to the difference in the lowest liquid production that can obtain economic benefits in reservoir development, there are significant differences in reservoir development effects with the same average daily liquid production. The determination of the lower limit of an effective reservoir needs to be comprehensively determined according to the specific geological conditions and existing data, combined with the applicability of different methods, to improve the accuracy of the calculation results. The origin and control factors of high-quality and effective reservoirs at medium-deep depths have always been the focus of petroleum geology research. Previous studies have shown that sedimentary facies, lithology and sorting control the original porosity of the reservoir, while diagenesis, abnormal formation pressure, granular film and early oil and gas filling are important control factors for the formation of high-quality reservoirs in the diagenetic process (Henares et al. 2014; Bjorlykke 2014; Zhao et al. 2019; Shi et al. 2021; Bai et al. 2021; Quandt et al. 2022). Dissolution is a common mechanism for forming deep high-quality clastic rock reservoirs (Zhong and Zhu 2008), but some researchers believe that under some geological conditions, dissolution pores only account for a small part of the overall pore volume, and there is no standard for the identification of dissolution pores (Taylor et al. 2010). The dissolution of unstable minerals such as feldspar leads to the redistribution of minerals and the formation of micropores, resulting in a decrease in permeability and affecting the physical properties of the reservoir (Yuan et al. 2015). When studying the genetic mechanism of medium-deep clastic reservoirs, we should not only consider the single factor that dissolution increases porosity and improves reservoir physical properties but also study various factors and their comprehensive control effects.

The Raoyang sag has experienced decades of exploration and development, with rich data such as drilling and coring, logging, oil test results, formation tests, physical property tests, thin-section identification and scanning electron microscopy. Currently, the exploration and development research in the Dawangzhuang area of Raoyang sag mainly focuses on shallow clastic rocks, and there is a lack of detailed discussion on the reservoir characteristics and control factors of medium-deep reservoirs, which is also a difficulty of the research (Cao et al. 2015). In recent years, many scholars have performed much research on the exploration of stratigraphic oil and gas reservoirs of the Shahejie Formation in the Raoyang sag from the aspects of sedimentation, sequence, accumulation and reservoir (Ni and Ji 2006; Zhang et al. 2017; Jin et al. 2016; Li et al. 2015; Zhao et al. 2011; Ji et al. 2006). The Shahejie Formation reservoir in the Dawangzhuang area is deeply buried, and the reservoir and reservoir forming modes are complex and diverse. Geological sweet points are relatively hidden, difficult to identify and have a high risk of exploration and evaluation (Zhang et al. 2016), which restricts the further in-depth evaluation of the middle and deep layers. Therefore, it is urgent to clarify the lower limit of reservoirs and determine the control factors of high-quality reservoirs, which is of great significance to guide the deployment of oil and gas exploration and increase reservoir efficiency. A large number of documents provide a large number of references for this study, which is not only limited to various geological data in the study area but also a lot of research on the application of the reservoir lower limit determination method and the special process in the process of reservoir diagenesis, which makes the results of this paper more reliable.

Geological setting

The Bohai Bay Basin is located southeast of the Eurasian plate and in the central area of the interaction of the three tectonic domains of the Pacific Ocean, the Tethys Ocean and the Paleo-Asian Ocean. The Raoyang sag is a secondary structural unit in the middle of the Jizhong depression in the Bohai Bay Basin, Eastern China. It is located in the middle of the Jizhong depression and belongs to a typical single fault sag structure. Structurally, the Dawangzhuang oilfield belongs to the Suning Dawangzhuang structural belt in the middle of the Raoyang sag, which is located in the extensional structural development belt (Fig. 1a). The study area is located in the southern Dawangzhuang oilfield, bounded by the Liu426 fault, including the Liu474 well area, the Liu483 well area, the Liu477 well area, the Liu70-39 well area and the Liu102 well area of the Liu70 fault block (Fig. 1b). The oil-bearing area is approximately 11 km^2. It is an area with rich oil and gas and high exploration efficiency in the Raoyang sag (Zhou et al. 2021). Two sedimentary subfacies, braided river delta plain and delta front, are mainly developed in the study area. The Shahejie Formation can be divided into four members (i.e. Es4, Es3, Es2, and Es1, from bottom to top) (Fig. 1c). Es1 and Es3 are the main exploration horizons in the medium-deep layers of the area. The target stratum of this study is mainly Es1–Es3.

Methods

Data, samples and experiments

The porosity and permeability data of 2186 sandstone reservoir plugs in the Shahejie Formation were collected from North China Oilfield Company of PetroChina. The porosity and permeability were measured with 3020-062 Helium Porosimeter and GDS-90F Gas Permeability meter, respectively. Porosity and permeability are measured in accordance with national standard GB/T29172-2012. The permeability of plug samples was measured using the differential pressure flow method. In order to reduce the gas slip effect, Kirschner correction was carried out. The inlet pressure, plug length and diameter will all affect the permeability value. In the process of sample processing, the extremely low deviation of sample length and diameter is ensured, and the accuracy of permeability value is ensured by extending the time of the test process. The error of permeability measurement is not more than ± 3%, and the accuracy is 0.01×10^{-3} μm^2.

Fifty-six thin sections were collected from 20 coring wells in the study area and studied by a Leica DM4 microscope to distinguish rock composition, pores and throats. Scanning electron microscope (SEM) observations were carried out on 28 samples using the Phenom ProX SEM to examine pore and throat types and pore filling cements, such as authigenic clay that cannot be clearly observed under a petrographic microscope. SEM images were collected at an accelerating voltage of 5 kV.

According to the industry standard SY/T5346-2005 (China), high-pressure mercury injection (HPMI) was conducted on 33 core plugs from 6 coring wells using the YG-97A mercury porosimeter. The above experiments were carried out in the Petroleum Geology Experiment Center of North China Oilfield Exploration and Development Research Institute.

The oil test data of 98 wells in the study area were collected from North China Oilfield Company of PetroChina, and the oil test was carried out by the downhole operation Department of North China Oilfield. The test method is Jiangston, and the process mainly includes: cleaning the impurities in the underground extraction part, drilling, deepening of the oil extraction pipe, testing pressure, temperature and other measures. Part of oil test data are shown in Table 1.

Calculation method of the lower limit of the effective reservoir physical properties

Oil test method

Taking the single-layer liquid production, that is, the sum of oil production and water production 1 *t/d*, as the standard, the effective reservoir and noneffective reservoir are divided, and their physical parameters are expressed in the same coordinate system. The physical property boundary between an effective reservoir and a noneffective reservoir is the lower limit of the effective reservoir physical property. The oil test method only needs to summarize the oil test data and the analysis and test data of coring wells. This method is closely combined with actual production and is suitable for determining the lower limit of the physical properties of various lithologic reservoirs with low–high porosity and permeability.

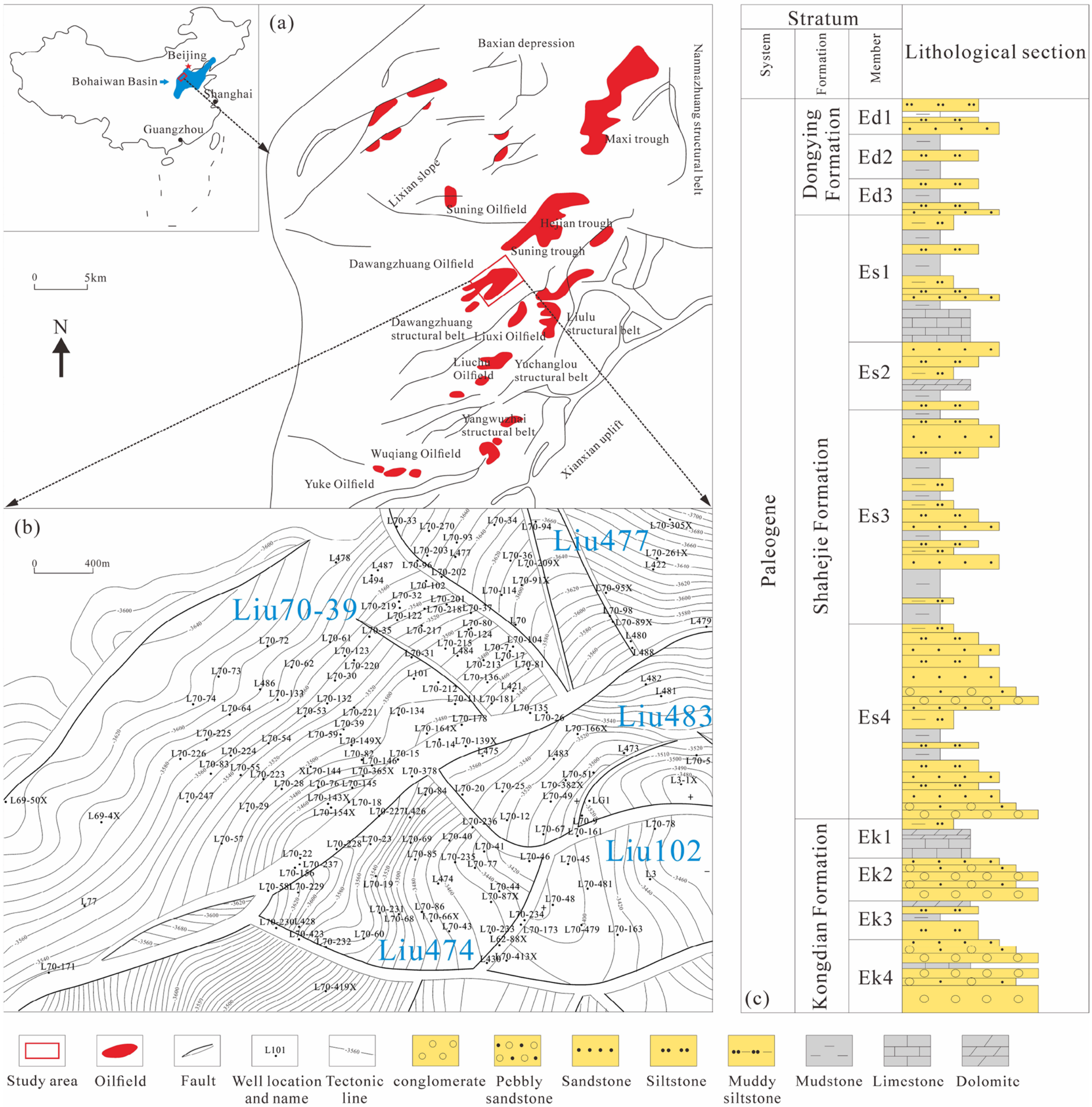

Fig. 1 Location of Raoyang sag (**a**), structure location of the study area (**b**) and stratigraphic column in the study area (**c**)

Metre oil production index test method

The relationship curve between the oil production index per metre and porosity or permeability is established to determine the lower limit value of reservoir physical properties. The intersection value between the relationship curve and abscissa axis is the lower limit value of porosity or permeability. Based on the data of the oil test and core physical property analysis, the test method objectively reflects the geological conditions and oil–gas seepage capacity of the reservoir, so it can better determine the lower limit of the physical properties of the effective reservoir. The formula of the oil production index per metre is as follows:

$$I = \frac{Q_0}{(\mathrm{Pe} - \mathrm{Pw})h}$$

Table 1 Oil test data in the study area

Well name	Layer	Sublayer Number	Well section/ m	Daily oil production/$_t$	Static pressure/ MPa	Oil test conclusion
L433	Es1	29–32	3376.6–3419.4	5.32	33.83	Oil–water layer
L433	Es1	21	3152.6–3155.4	0.21	31.54	Water layer
L433	Es1	22	3178.6–3180.6	5.04	32	Oil–water layer
L485	Es1	22–30	3223.6–3282	33.9	32.54	Oil layer
L459	Es2	21	3120–3136	79.2	33.81	Oil layer
L438	Es1	10–13	3245–3267.2	2.1	32.57	Oily water layer
L438	Es1	8–9	3203.2–3220	28.4	32.16	Oil–water layer
L70-39	Es3	41–42	3608.6–3616	106.5	37.78	Oil layer
L101	Es3	89, 90	3792.6–3801.4	5.3	38.88	Oil–water layer
L101	Es3	83	3753–3758	0.17	38.61	Oily water layer
L488	Es1	31	3170–3178.6	7.42	31.14	Oily water layer
L488	Es3	115–117	3688.8–3741.8	16.5	33.4	Oil–water layer
L488	Es3	120	3728.8–3741.8	29.7	36.96	Oil layer
L453	Es3	26, 27	3081.4–3102.6	11.7	35.76	Oil layer
L491	Es3	75–79	3747.7–3830.6	2.3	37.39	Oil layer
L491	Es3	85	3826–3830.6	0	37.01	Dry layer
L70-94	Es1	50	3394.6–3399	10.4	33.5	Oil–water layer
L492	Es3	48	3451.1–3457	0.78	40.63	Oil–water layer
L70-29	Es3	47	3461.8–3467.6	7.42	31.14	Oil–water layer
L70-84	Es1	34–36	3258.4–3280	14	2.2	Oil–water layer

where Q_0 is the oil production, Pe is the formation pressure, Pw is the bottom hole flow pressure and h is the thickness.

Frequency curve intersection method

A method to determine the lower limit of reservoir physical properties by calculating the percentage of the loss of reservoir oil storage capacity and oil permeability in the total accumulation. The physical property distribution frequency curves of the effective reservoir and noneffective reservoir are drawn on the same coordinate system. The intersection value of the two curves is the lower limit of the effective reservoir physical properties. This method requires much analysis and test data of porosity and permeability. Due to the great differences in the physical properties of different reservoirs and lithologies, this method is suitable for reservoirs with the same lithology and a good correlation between porosity and permeability.

Results

According to the data of physical property data and oil test data in the study area, the lower limit of the effective reservoir physical property of the Shahejie Formation in the Dawangzhuang area is obtained by sections. The lower limit of the effective reservoir physical properties in the Dawangzhuang area of the Raoyang sag is calculated by the oil test method. The lower limits of porosity at depths of Es1, Es2 and Es3 are 9.64, 9.53 and 9.74%, respectively; the lower limits of permeability are 1.04×10^{-3}, 0.86×10^{-3}, and 0.53×10^{-3} μm^2, respectively (Fig. 2).

The lower limit values of effective porosity at Es1 and Es3 depths in the Dawangzhuang area of the Raoyang sag are 9.46 and 8.59%, respectively; the lower limit of permeability at Es1 is 0.87×10^{-3} μm^2 (Fig. 3 and Table 2).

The lower limit of the effective reservoir physical properties in the Dawangzhuang area of the Raoyang sag is obtained by the frequency curve intersection method. The lower limits of porosity at Es1, Es2 and Es3 are 10.09, 9.34 and 8.23%, respectively; the lower limits of permeability are 1.73×10^{-3}, 1.51×10^{-3}, and 0.64×10^{-3} μm^2, respectively (Fig. 4 and Table 2).

Based on the above methods, the lower limit of reservoir physical properties in different layers of the Shahejie Formation in the Dawangzhuang area of the Raoyang sag can be obtained (Table 2). The above three methods to calculate the lower limit of effective reservoir physical properties have certain application scopes and limitations. The frequency curve intersection method uses logging interpretation data, which can better reflect the regularity, but the accuracy is insufficient. The oil test method and test method calculate the lower limit of physical properties based on the measured physical properties combined with the oil test data, which has high accuracy,

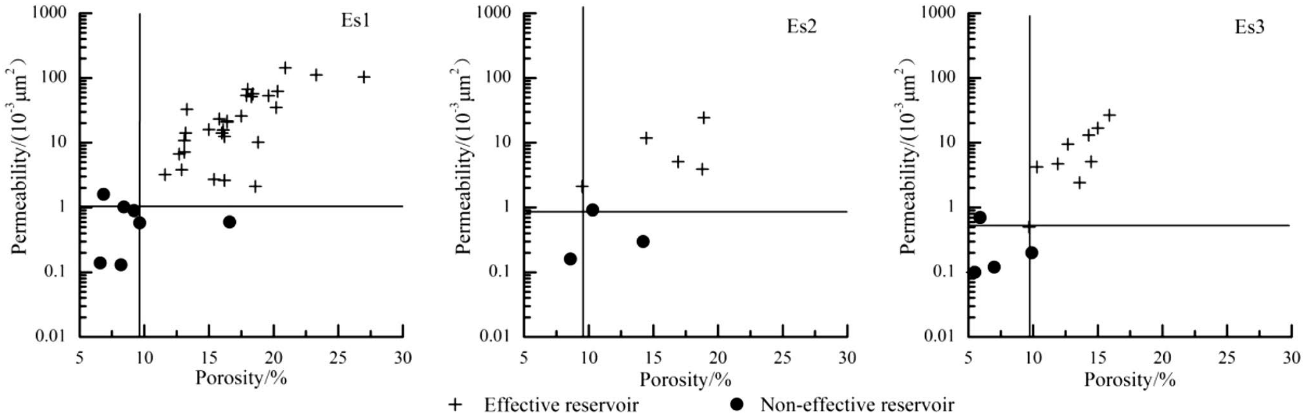

Fig. 2 Lower limit of physical properties determined by the oil test method

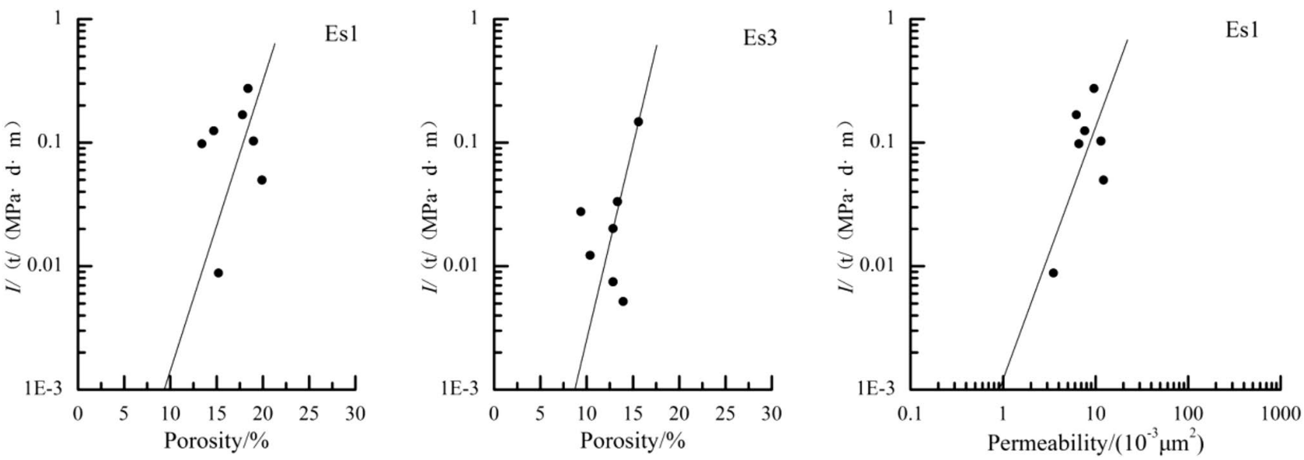

Fig. 3 Lower limit of physical properties determined by the oil production index test method

Table 2 Lower limit of reservoir physical properties of the Shahejie Formation in the Dawangzhuang area, Raoyang sag

Method	Layer	Porosity/%	Permeability/10^{-3}μm^2
Oil test method	Es1	9.64	1.04
	Es2	9.53	0.86
	Es3	9.74	0.53
Test method	Es1	9.46	0.87
	Es3	8.59	–
Frequency curve method	Es1	10.09	1.73
	Es2	9.34	1.51
	Es3	8.23	0.64

but the data are not easy to obtain and have many restrictions. To eliminate the error caused by the original data error, insufficient data or calculation method of a single method, the analytic hierarchy process (AHP) is introduced to decompose the complex problem into several levels and factors, and the weights of different methods can be obtained by comparing and calculating the factors.

Through the steps of establishing the index hierarchy, building the Comparison matrix, ranking and consistency inspection, the weight vectors of the three methods are obtained, and the weights are calculated by MATLAB software (Table 3). According to the principle of AHP, the lower limit of porosity was 9.73, 9.44 and 8.85% at depths of Es1, Es2 and Es3, respectively. The lower limit of permeability was 1.21×10^{-3}, 1.18×10^{-3} and 0.59×10^{-3} μm^2. Because the tight sandstone reservoir is greatly affected by compaction, the lower limit of the Shahejie Formation reservoir generally decreases with the increase in burial depth.

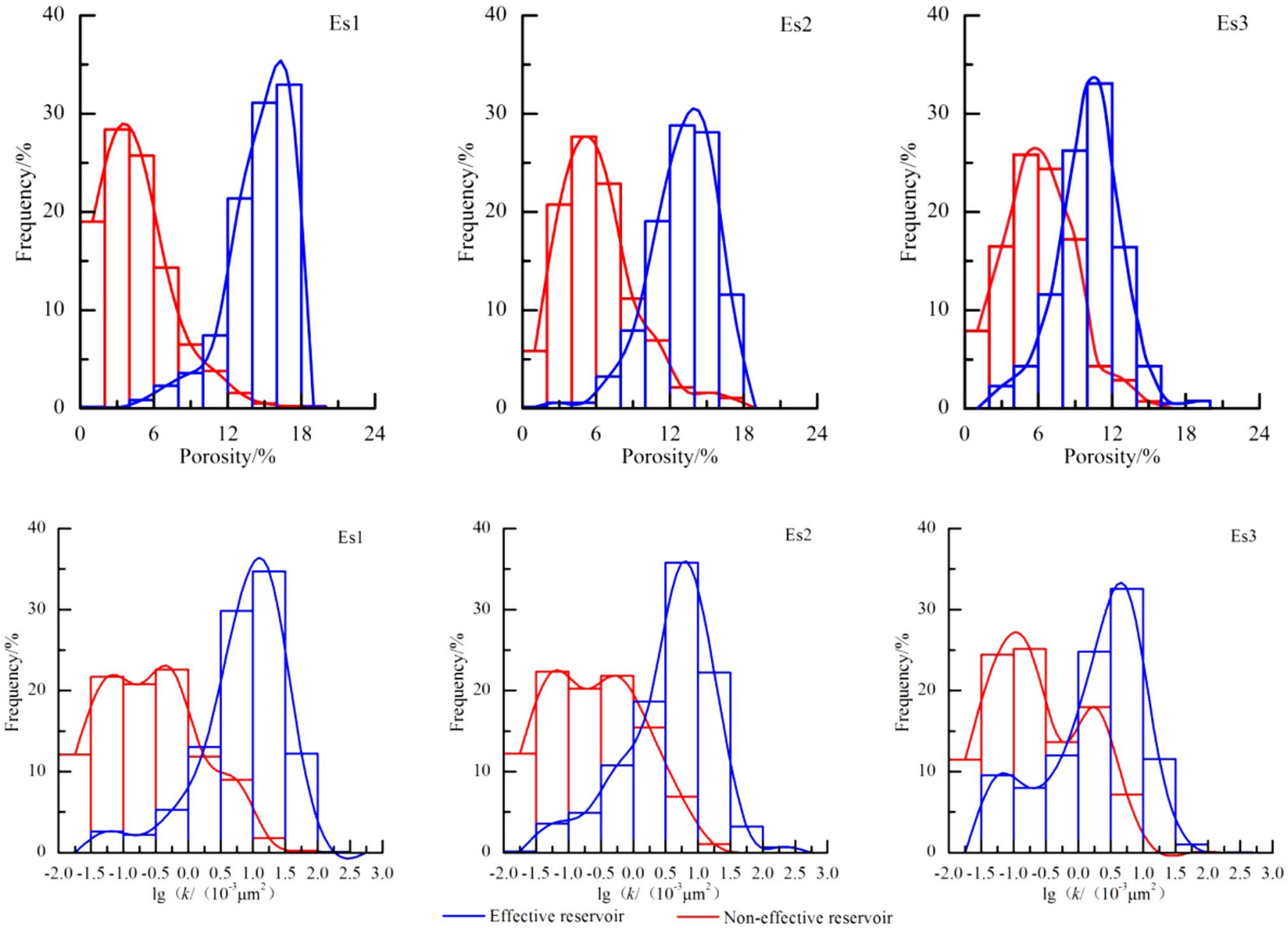

Fig. 4 Lower limit of the physical properties determined by the frequency curve intersection method

Table 3 Comparison matrix of three methods to determine the lower limit of reservoir

Method	Oil test method	Test method	Frequency curve method	Weight
Oil test method	1	2	3	0.5396
Test method	1/2	1	2	0.2970
Frequency curve method	1/3	1/2	1	0.1634

Analysis of the controlling factors of effective reservoirs in the Shahejie Formation

Porosity and permeability are important parameters for analysing and discussing effective reservoir control factors. By analysing the distribution law of reservoir physical properties at different depths, it is found that the physical properties of the 3200–3300 m, 3500–3700 m and 4200–4300 m sections in the study area are good, which is an obvious reservoir sweet point (Fig. 5). Reservoir formation is affected by many factors. The burial depth of the Shahejie Formation in the Dawangzhuang area of the Raoyang sag is deeper, and the control factors of the effective reservoir are more complex and are mainly controlled by factors such as formation pressure, sand body thickness and diagenesis.

Control of formation abnormally high pressure on reservoir development

The abnormally high pressure not only inhibits the development of compaction, thus protecting the primary pores and making the medium-deep reservoirs have good physical properties but also makes the formation water

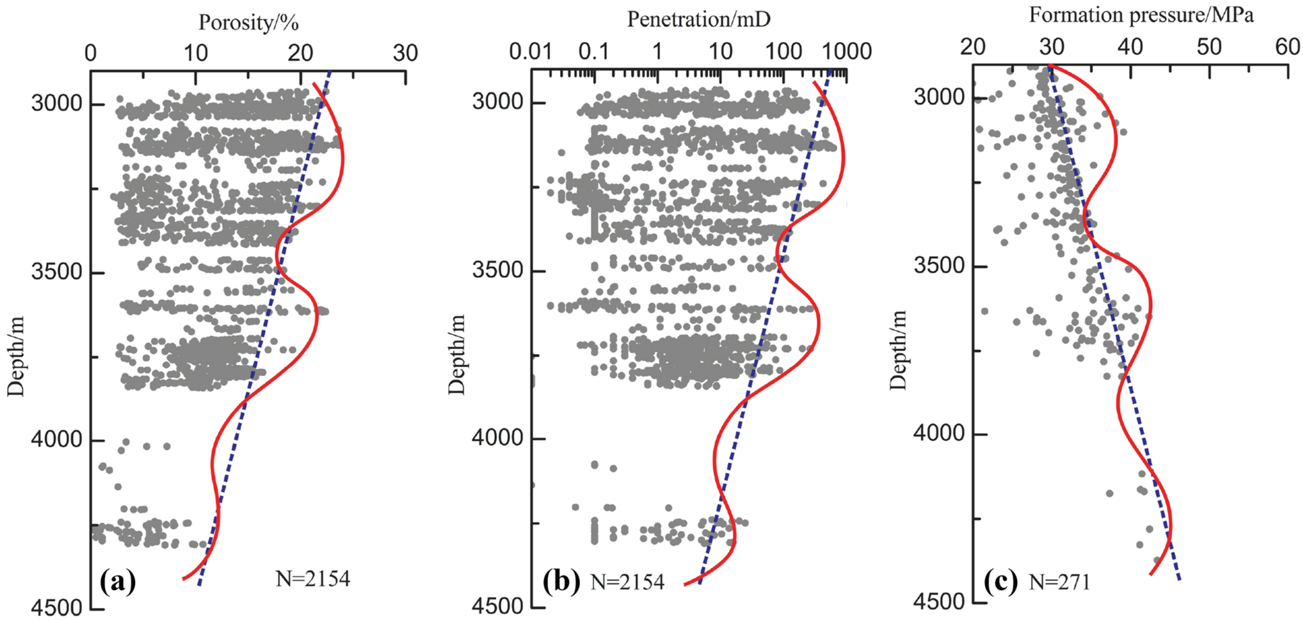

Fig. 5 Distribution of reservoir physical properties and formation pressure in the Dawangzhuang area of the Raoyang sag

environment acidic for a long time, promotes dissolution and improves the reservoir conditions by controlling the transformation of clay minerals and inhibiting the thermal evolution of organic matter. In addition, it can also provide power for oil and gas migration (Meng et al. 2008; Chen et al. 2002). The formation pressure data show that the Shahejie Formation in the Dawangzhuang area of the Raoyang sag has abnormal high-pressure development. It is an abnormally high-pressure development zone at depths of 3000–3300 m, 3500–3800 m and 4200–4300 m and has a good corresponding relationship with the vertical distribution law of reservoir physical properties, indicating that overpressure promotes the formation of high-quality reservoirs to a certain extent (Fig. 5).

The compaction of the Shahejie Formation in the study area is strong as a whole, but the compaction is weak at the depth of some areas, and the pore structure is well preserved. Abnormally high pressure is an important factor to inhibit compaction and promote the development of later dissolution. The variation trend of physical properties of well 1101 is basically consistent with that of formation pressure coefficient. Areas with formation pressure coefficient greater than 1.2 are easier to form effective reservoirs. Through the observation of cast thin sections, it can be found that the compaction in the underdeveloped area of abnormally high pressure is strong, the particle contact type is mainly line to line, the preservation of primary pores is poor, and the dissolution transformation is not obvious. The rapid accumulation of sediments leads to the formation of local early abnormally high pressure. The existence of abnormally high pressure preserves the primary pores to a certain extent, which is conducive to the dissolution and transformation of reservoirs by acidic fluids such as organic acids in the later stage (Fig. 6).

Control of sand body thickness on reservoir development

According to the statistics of the single-layer thickness of the Shahejie Formation sand body in the study area, the distribution characteristics are as follows: thicknesses < 2 m account for 29.89%, 2 ~ 4 m account for 36.66%, 4 ~ 6 m account for 20.17%, 6 ~ 8 m account for 6.80%, 8 ~ 11 m account for 2.19% and > 10 m account for 4.25% (Fig. 7a). The sedimentary thickness of the braided river delta front sedimentary subfacies sand body is medium, which reflects the characteristics of stable water flow and active sedimentation at that time. According to the statistics of the proportion of effective reservoirs of sand bodies with different thicknesses, the proportions of effective reservoirs of 0 ~ 2, 2 ~ 4, 4 ~ 6, 6 ~ 8, 8 ~ 10 and > 10 m sand bodies are 54.42, 75.08, 78.89, 78.97, 84.27 and 87.86%, respectively (Fig. 7b). The proportion of the effective reservoir of the sand body is positively correlated with the thickness. The proportion of effective reservoirs of sand bodies with thicknesses greater than 2 m can reach more than 75%; that is, the greater the thickness of a single layer of sand body is, the better the reservoir effectiveness of the sand body and the easier it is to develop an effective reservoir. The single-layer sedimentary thickness of the sand body has a certain relationship with the sedimentary microfacies. For example, the single-layer thickness of sedimentary microfacies of

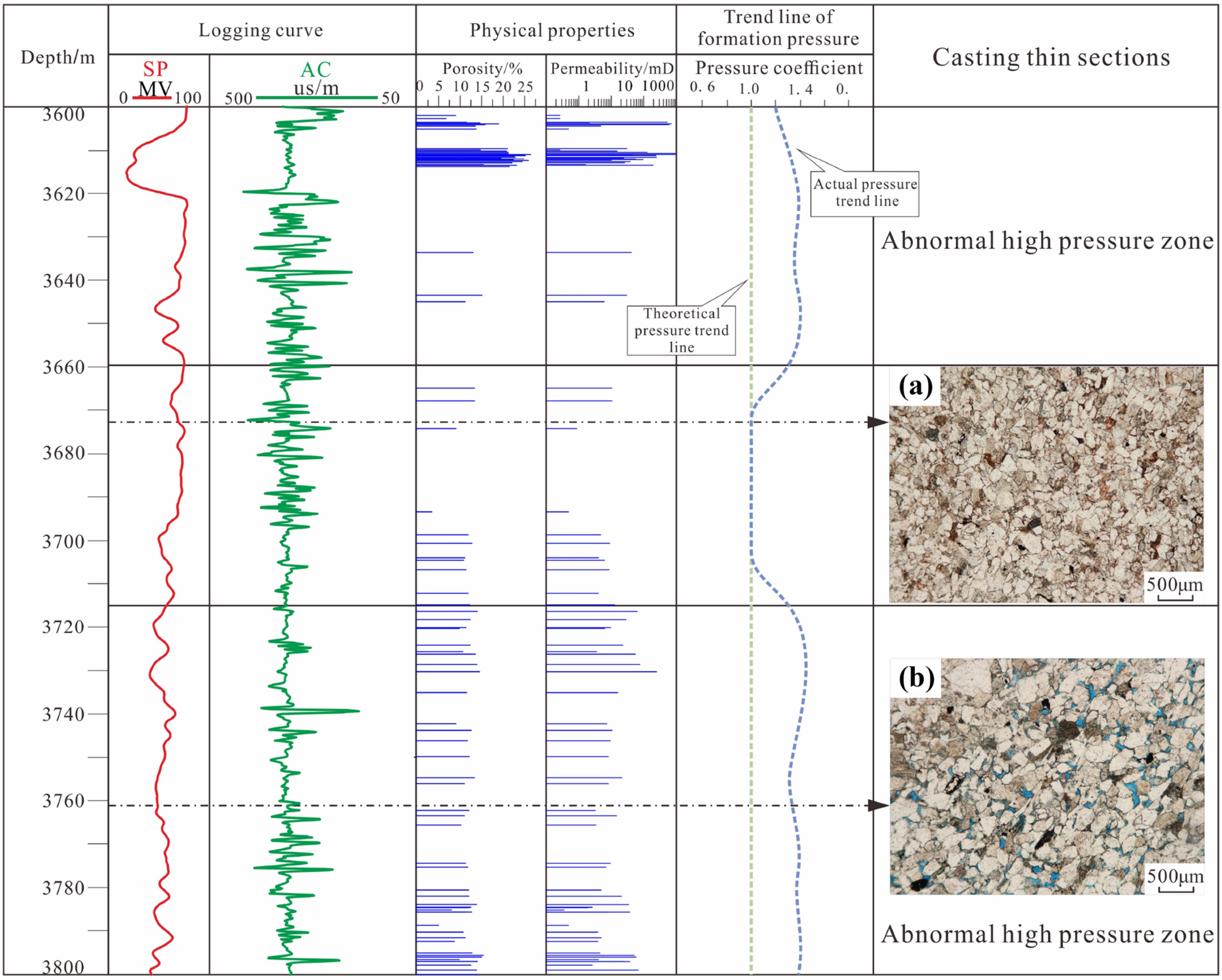

Fig. 6 Relationship between formation pressure and reservoir physical properties of well L101 in the Dawangzhuang area of the Raoyang sag (**a**: Well L101, 3672.53 m, abnormally high-pressure underdeveloped area, with strong compaction and almost loss of primary pores; **b:** Well L101, 3760.77 m, is an abnormally high-pressure development area, with good preservation conditions for primary pores)

underwater distributary channels and estuary bars is generally large, and the single-layer thickness of sedimentary microfacies of sheet sand and underwater distributary bay is small. Therefore, the greater the thickness of the sand body is, the stronger the sedimentary hydrodynamics, the better the physical properties of the reservoir, and the easier it is to develop an effective reservoir.

Control of diagenesis on reservoir development

Compaction

The target horizon in the study area has a large burial depth and fast burial speed. The Paleogene sedimentation rate is 140 m/Ma, the Neogene sedimentation rate is 129 m/Ma, and the Quaternary sedimentation rate is 260 m/Ma (Wang and Li 2014; Gao et al. 2014). It is found that the sandstone clastic particles are in line and point line contact by observing the cast thin section. Plastic particles such as mica are compacted and deformed, and rigid particles are broken locally (Fig. 8). The compaction is relatively strong. According to the cross plot of the pore reduction rate of reservoir compaction and cementation (Fig. 9a), the pore reduction rate caused by compaction can reach 20–75%, and the data points above 50% are denser. Therefore, compaction and pore reduction are the main factors for pore reduction in the Dawangzhuang area, and anti-compaction has become a prerequisite for the development of high-quality reservoirs in the Raoyang sag.

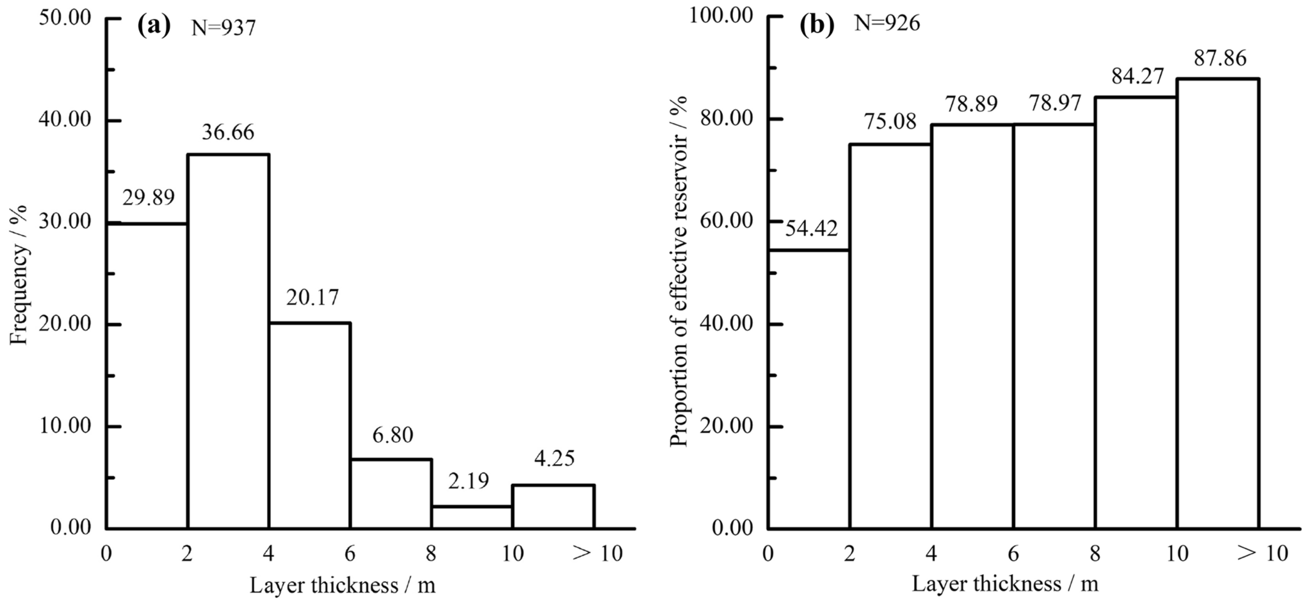

Fig. 7 Distribution characteristics of the single-layer thickness of different sand bodies in the Dawangzhuang area of the Raoyang sag (**a**) and the proportion of effective reservoirs under sand bodies with different thicknesses (**b**)

There are many factors affecting compaction, such as burial depth, sediment composition, grain size, sorting, early cementation, dissolution, geothermal gradient and abnormally high-pressure zones (Dar et al. 2022; Wang et al. 2022). These factors will cause the porosity development zone to be different from the normal compaction trend, which is of great significance to reservoir research. Compared with other areas in the Raoyang sag, the content of rigid component quartz in the Dawangzhuang area is lower, which enhances the influence of compaction on reservoir densification. As seen from the distribution map of rock composition content in different layers (Fig. 9b), with increasing burial depth, the quartz content decreases, which leads to the poor anti-compaction ability of medium-deep reservoirs.

Cementation

Cementation is common in the Shahejie Formation in the Dawangzhuang area. The types of cements are mainly calcareous, siliceous and clay minerals, with less content of other cements (Fig. 8). The development of late cementation determines the physical properties of the current reservoir (Zhang et al. 2011). Through statistics on the percentage of cement and reservoir physical property data in the Dawangzhuang area of Raoyang sag (Fig. 10a), it can be found that when the proportion of cement is 0 ~ 8, 8 ~ 16, 16 ~ 24 and 24 ~ 32%, the effective physical property percentages of the reservoir are 85.71, 81.58, 55.93 and 28.20%, respectively. Cementation has an obvious adverse impact on the development of reservoirs. The control effect of different cementation types on the reservoir is also different. The cementation types in the Dawangzhuang area mainly include basement cementation, pore cementation and contact cementation (Fig. 10b). Among them, the content of basement cementation filler is large, which generally represents the sedimentary characteristics of rapid accumulation of high-density flow and poor sorting. Therefore, the reservoir quality is poor, and the average porosity is only 10.81%. The sedimentary conditions of pore cementation and contact cementation are relatively stable, the content of cement is small, the reservoir quality is relatively good, and the average porosity can reach 12.96 and 14.71%.

The content of cement is closely related to the physical properties, and it is easy to form a dense cemented layer near the contact interface between sand and mudstone, and the volume fraction of carbonate cement is high (Fig. 11). In the reservoir characterized by sand and mudstone interbedding, the cement in sandstone has obvious differential distribution characteristics due to the diagenesis of interbedded mudstone, which controls the distribution of reservoir physical properties; from the edge of the sand body to the centre of the sand body, the volume fraction of cement in sandstone gradually decreases, and the reservoir porosity and permeability gradually increase. When it is far from the sand mudstone interface, the reservoir physical properties tend to be stable. For a sand body with a certain thickness, the development of an early carbonate dense cementation layer on the one hand prevented the formation of carbonate cement far from the contact interface between the sand

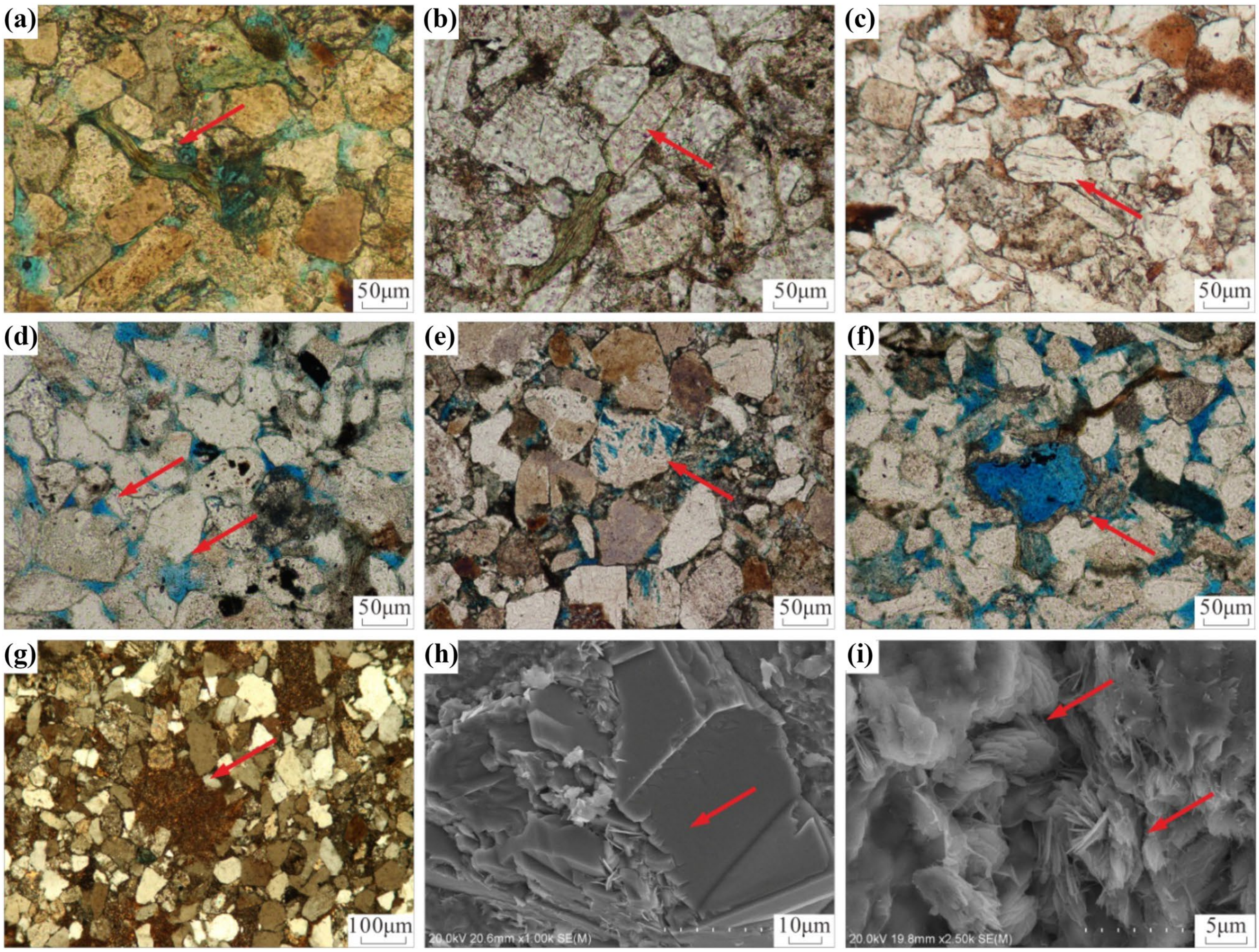

Fig. 8 Diagenetic characteristics of the Shahejie Formation reservoir in the Dawangzhuang area, Raoyang sag (**a**: Well L18-24, 2694.74 m, plastic particles, bending deformation, casting sheet; **b** Well L494, 3772.86 m, with sandstone particles in line-to-line contact locally and thin cast body; **c** Well L70-114, 3755.86 m, rigid particles are broken, and the cast body is thin; **d** Well L93, 3534.88 m, intergranular corrosion, cast thin section; **e** Well L17-50, 3091.55 m, feldspar dissolution in grains, cast thin section; **f** Well L70-93, 3362.84 m, feldspar dissolution, formation of super pores, dissolution of soluble components in rock cuttings, thin cast body; g: Well L487, 3683.95 m, carbonate cementation, cast thin section; **h** Well L70-114, 3825.56 m, quartz enlarged edge, SEM; **i** Well L101, 3760.77 m, clay mineral cement, authigenic illite and chlorite, SEM)

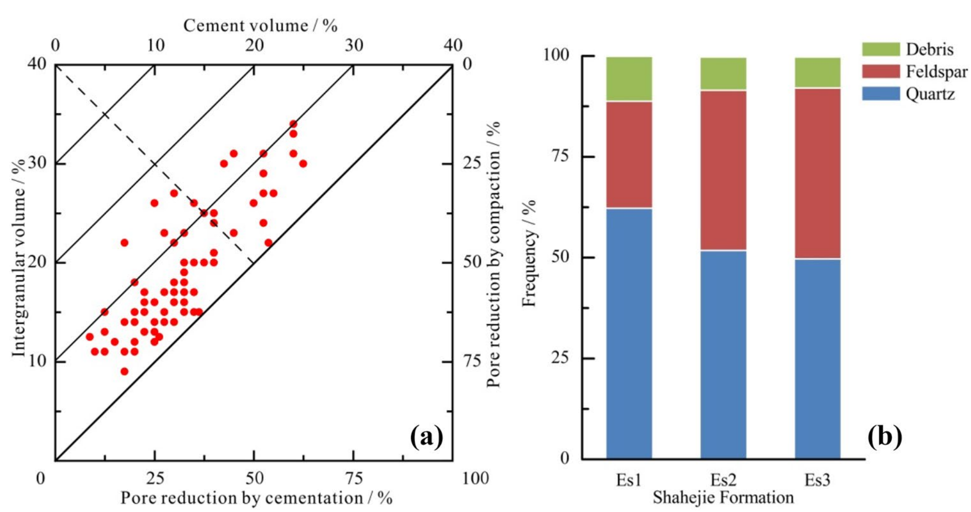

Fig. 9 Cross plot of pore reduction rate (**a**) and distribution map of rock composition content (**b**) in the Dawangzhuang area of Raoyang sag

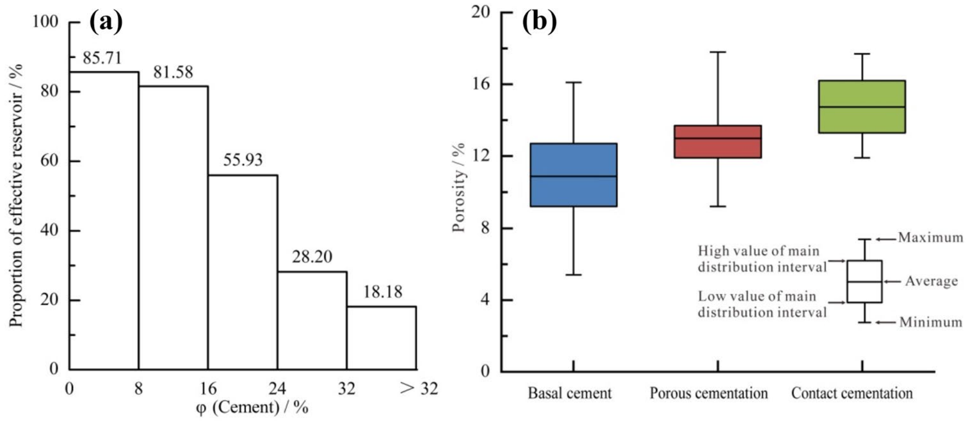

Fig. 10 Relationship between the volume fraction of different cements and the proportion of effective reservoirs (**a**) and box diagram of the relationship between different cementation types and reservoir physical properties (**b**)

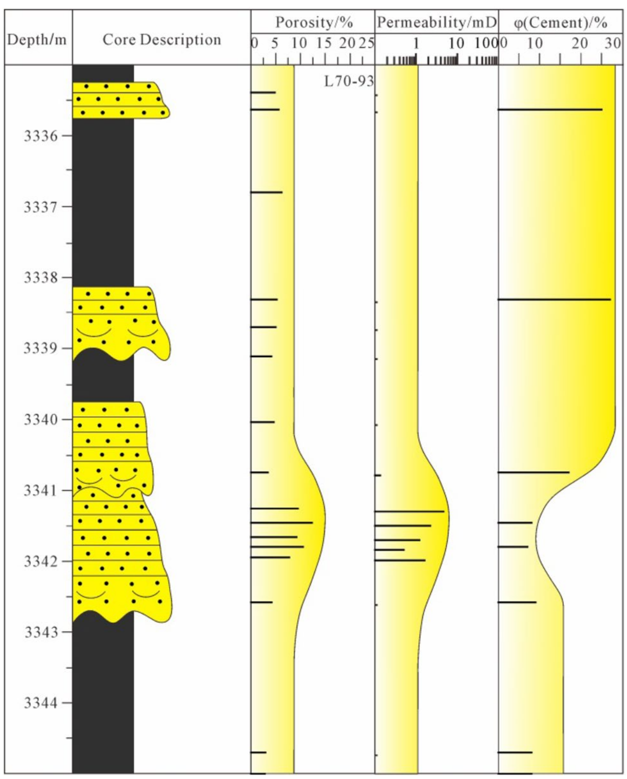

Fig. 11 Cement content and physical properties of different sand bodies in the Dawangzhuang area of the Raoyang sag

and mudstone; on the other hand, it was also conducive to protecting the abnormally high pressure of the formation. At the same time, it can also enhance the compressive capacity of the rock itself to a certain extent, making it conducive to the formation of effective reservoirs.

Dissolution

Dissolution and the formation of secondary pores are the focus of deep petroleum geology. The dissolution of the Shahejie Formation in the study area is widely developed, and secondary pores can account for nearly 70% of the total pores; mainly feldspar dissolution and intragranular and intergranular dissolution are developed, with occasional super pores (Fig. 8). In addition, the dissolution of some quartz cuttings and carbonate cement can be seen. Through the statistics of the capillary pressure test results of typical well L101 in the Dawangzhuang area (Table 4) and selecting samples with similar physical properties, it was found that there are two obvious peaks in the pore throats of reservoir sandstone (Fig. 12), that is, the primary intergranular pores with relatively small pore throat radii and relatively large dissolution pores, and their average values were 1 ~ 1.6 and 4 ~ 6.3 μm, respectively.

The acid fluid filling after the maturity of source rocks in the middle stage of diagenetic evolution is the main factor

Table 4 Capillary pressure test sample

Sample number	Depth/m	Porosity/%	Mean pore throat diameter/μm	Sorting coefficient	Median pressure/Mpa	Withdrawal efficiency/%	Lithology
Sample-1	3356.00	16.3	4.52	15.93	9.90	97.49	Sandstone
Sample-2	3494.20	17.0	9.59	21.65	0.25	18.34	Sandstone
Sample-3	3634.01	10.4	5.39	20.40	11.22	15.30	Sandstone
Sample-4	3641.95	14.3	5.91	24.35	18.16	21.00	Sandstone
Sample-5	3643.50	15.8	5.68	4.27	5.12	18.80	Sandstone
Sample-6	3644.05	15.4	6.00	22.35	6.71	17.50	Sandstone

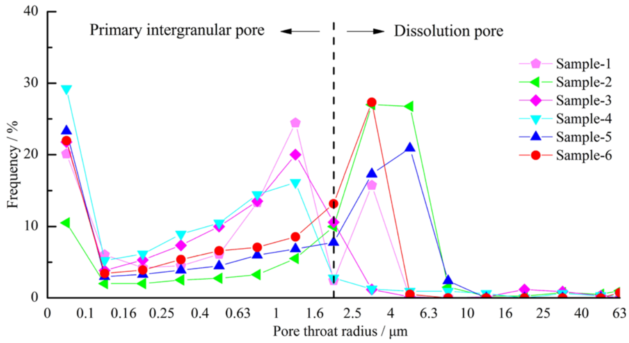

Fig. 12 Distribution law of pore throat radius

promoting the occurrence of dissolution (Jin et al. 2018). Because the residual primary pores can provide channels for the dissolution fluid and promote the development of secondary dissolution pores, the preservation of primary pores can also promote the development of secondary dissolution pores. With the increase in the content of soluble feldspar in the reservoir rock, the influence of dissolution was more obvious, and the physical properties of the reservoir tend to improve (Fig. 13). Through the above analysis, it can be concluded that dissolution in the study area has an obvious impact on deep reservoirs, and the formed dissolution pores are the main reservoir space type of deep reservoirs and the key factor promoting the development of deep effective reservoirs.

Relationship between diagenesis and reservoir evolution

Based on the analysis of cast thin section, scanning electron microscope and rock and mineral fabric, it is considered that the diagenetic sequence of the Shahejie Formation reservoir in the Dawangzhuang area is in the middle diagenetic stage A, and some of it is in the middle diagenetic stage B (Fig. 14). There are many diageneses in the Shahejie Formation in the Dawangzhuang area, which has a significant impact on the porosity and permeability of medium-deep reservoir properties. The diagenesis evolution sequence is: (a) early compaction, (b) early chlorite cementation, (c) early feldspar dissolution, calcite cementation, (d) quartz overgrowth, clay cementation, feldspar dissolution, (e) montmorillonite illite and (f) late iron-bearing carbonate cementation. The main destructive diagenesis is mainly compaction and cementation, and the constructive diagenesis is dissolution. Specifically, with increasing depth, compaction destroys the pore structure of the sand body, the secondary pores generated under by two-stage dissolution effectively improve the physical properties of the reservoir, and multistage cementation densifies the reservoir. Late cementation has a greater destructive effect on effective reservoirs because it is later than the second organic acid dissolution.

Conclusion

There are some limitations in using oil test method, metre oil production index test method or frequency curve intersection method, respectively. Using AHP, the weights of each method were calculated. The lower physical limit of the effective reservoir of the Shahejie Formation in the Dawangzhuang area is determined comprehensively. On this basis, the controlling factors of high-quality reservoir development of the Shahejie Formation in the Dawangzhuang area of the Raoyang sag are analysed from three aspects: formation pressure, sand body thickness and diagenesis. The research can draw the following conclusions:

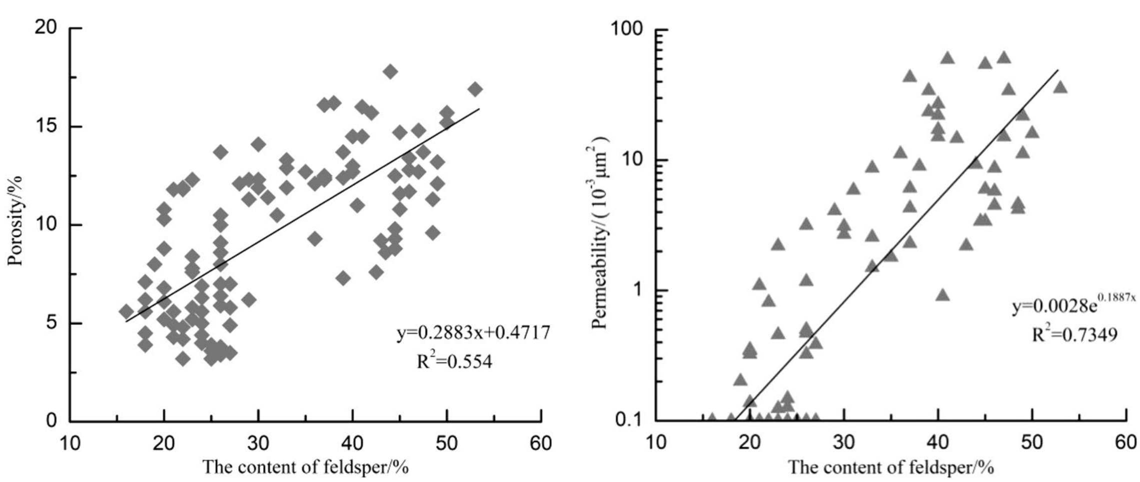

Fig. 13 Variation in physical properties with feldspar content

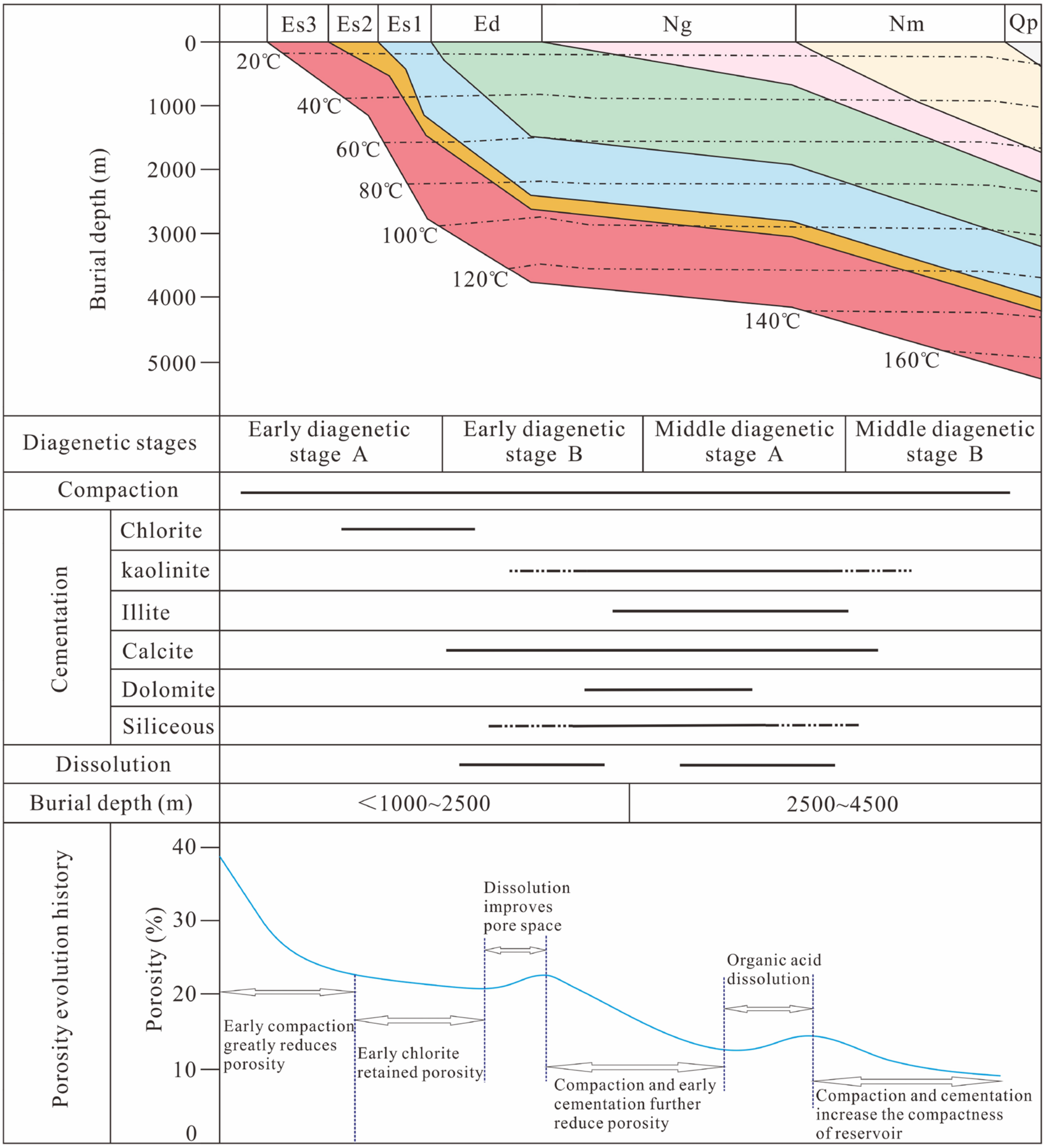

Fig. 14 Diagenetic evolution sequence of the Shahejie Formation reservoir

1. The lower limit of the porosity of Es1, Es2 and Es3 in the Dawangzhuang area is 9.73, 9.44 and 8.85%, respectively; the lower limit of permeability is 1.21×10^{-3}, 1.18×10^{-3} and 0.59×10^{-3} μm^2, respectively.
2. Effective reservoirs are easier to form in areas where the formation pressure coefficient is greater than 1.2. Formation overpressure inhibits the development of compaction, thus protecting the primary pores. The thicker the sand body is, the more conducive it is to the formation of high-quality reservoirs. The proportion of effective reservoirs of sand bodies with thicknesses greater than 2 m can reach more than 75%.
3. Diagenesis comprehensively affects the development of high-quality reservoirs. The porosity reduction rate caused by compaction and cementation is 20–75 and 8–60%, respectively. Compaction porosity reduction is the main factor of reservoir porosity reduction. Cementation further densifies the reservoir. The average pore throat radius of dissolution pores can reach 4 ~ 6.3 μm, and the secondary pores produced by dissolution effectively improve the physical properties of the reservoir.

4. The diagenetic sequence of the Shahejie Formation reservoir in the Dawangzhuang area is in the middle diagenetic stage A, and part of it is in the middle diagenetic stage B. The late cementation is later than the second organic acid dissolution, which has a greater damage effect on the effective reservoir.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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