Research Article

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Selecting fracturing interval for the exploitation of tight oil reservoirs from logs: a case study

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Abstract: The optimal selection of fracturing interval for the exploitation of tight oil reservoirs is very important for formulating a development program. In this study, the reservoir quality and the reservoir fracability are evaluated, and the criteria for the optimal selection of the fracturing interval are established, using the tight reservoir in the the Qing I Member of Qingshankou Formation in the Daqingzijing Oilfield of China as the study site. The results indicate that the porosity, the oil saturation and the effective thickness of tight reservoir are keys to optimizing the fracturing interval. The brittleness index and the difference coefficient among the horizontal stresses in the reservoir have a strong influence on fracability. The stress difference coefficient in the reservoir is smaller and the reservoir develops microfractures, the complex mesh fractures are easier to occur during fracturing. The stress difference between the reservoir and the surrounding bed is small and the thickness of the surrounding bed is thin, it is easy to communicate with adjacent oil-bearing layers when fracturing.

Keywords: Tight oil; Reservoir; Fracturing interval; Optimal selection; Logging

Terminology

GR Natural gamma ray log
SP Spontaneous potential log
CAL Caliper log
RLLD Deep dual laterolog
RLLS Shallow dual laterolog
MSFL Microspheres focused log
AC Compensated acoustic log
DEN Compensation density log
CNL Compensated neutron log
$\Delta \mathbf{t}_S$ S-wave time difference log
a, b Index relating to lithology

1 Introduction

Tight oil has become a key field in the exploration and development of unconventional oil resources in China [1]. Tight oil development practices have shown that even if a tight reservoir has stable sedimentation, a continuous distribution on the plane and minor changes in porosity, the production following fracturing is very different [2–4]. It indicates that the fracturing of tight oil reservoir determines whether tight oil can be commercially produced [5–7]. On this account, selecting fracturing interval in tight oil reservoir should consider not only the reservoir quality, but also the reservoir fracability.

Studies have shown that hydraulic fracturing is an effective way to increase the production of tight oil reservoir. The selection of layers has a direct impact on the fracturing effect [8, 9]. Currently, oilfields select the fracturing interval based on experience or the reservoir evaluation results, which can't guarantee good production following fracturing [10, 11]. Accordingly, the reservoir quality and the reservoir fracability are evaluated using logging data, and then the fracture interval of tight oil reservoirs is selected.

2 Geological setting

The research area is located in the eastern Daqingzijing Oilfield in the Songliao Basin in northeastern China (see Figure 1). The Daqingzijing Oilfield is structurally controlled by the Daqingzijing palaeohigh [12]. The oblique west wing fault is relatively developed. Faults are relatively devel-

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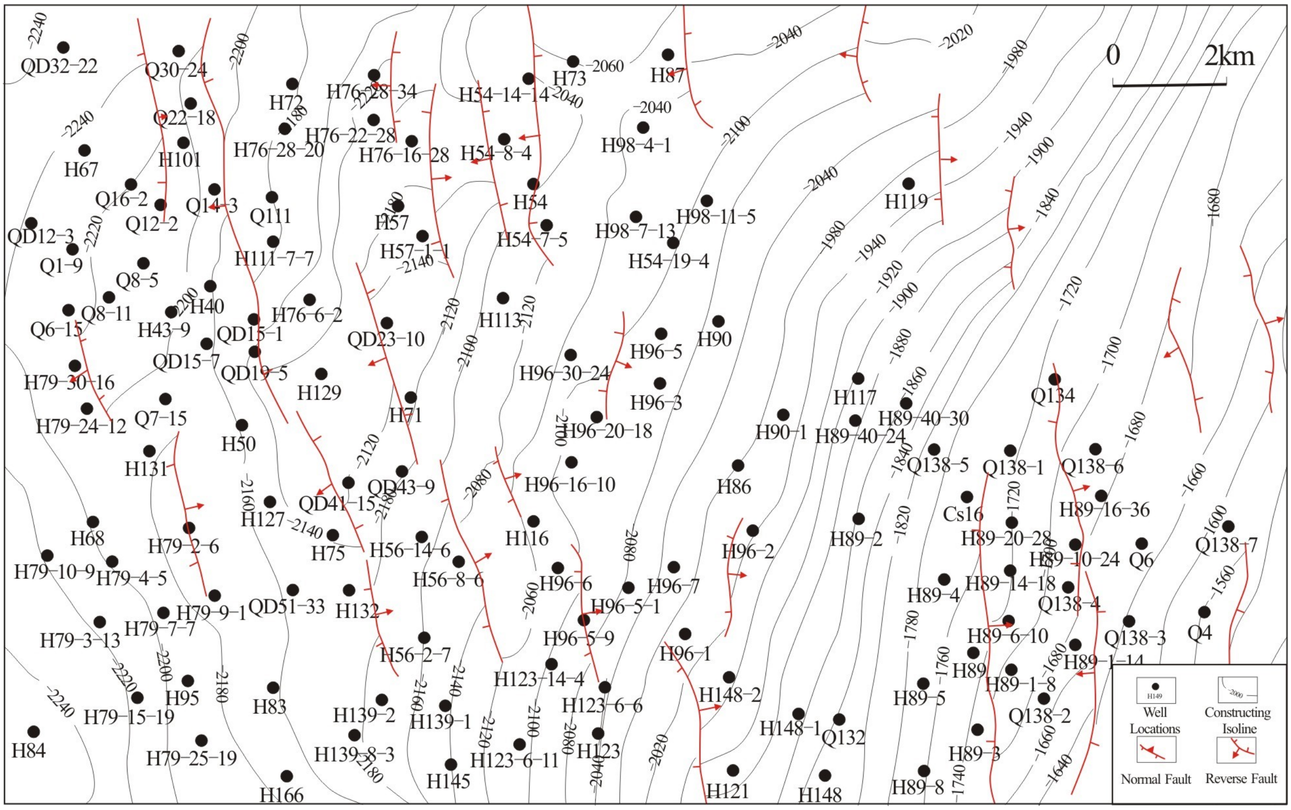


Figure 1: The location map of the work area and the well

oped to the west wing of the syncline [13]. A series of north-northwest normal faults are developed at the axis of the syncline, forming a complex fault zone. A large normal fault is developed in the north-south direction of the eastward wing.

In February, 2004, Well H148 was drilled in H89 block to the southeast of the Daqingzijing Oilfield. Oil patch signs were observed in the central part of the Qing-1 Member of the Qingshankou Formation of the well. Reservoirs in the Qing-1 Member of the Qingshankou Formation came with poor physical properties, complex pore structures and small throat radius as well as low production. Due to the poor physical properties of tight oil reservoirs and the relatively backward fracturing technology in the research area, the oil field has not been developed. Until 2016, the tight oil reservoir of Well H56-16-4 achieved a capacity of 4.7 m^3/day by carrying out large volume fracturing tests. With such a high yield of the well, the Jilin oilfield made tight oil in the The Qing I Member of Qingshankou Formation a major layer for subsequent development.

3 Workflow and method discription

3.1 Workflow

The main processes used in this case study are described and graphically explained on the Figure 2. The workflow was divided into three phases, which are listed below.

(A) Reservoir quality evaluation

Firstly, the porosity is calculated using DEN, CNL and AC logs. Secondly, the oil saturation is calculated, using Rt log and porosity, combined with the parameter of a, b, m, n and Rw. Thirdly, the effective thickness of tight reservoir is determined, according to the study area reservoir porosity and oil saturation limit.

(B) Evaluation of reservoir fracability

Firstly, the natural fracture is evaluated using FMI image. Secondly, using AC, Δt_s and DEN logs, the maximum and minimum horizontal principal stress are calculated, and

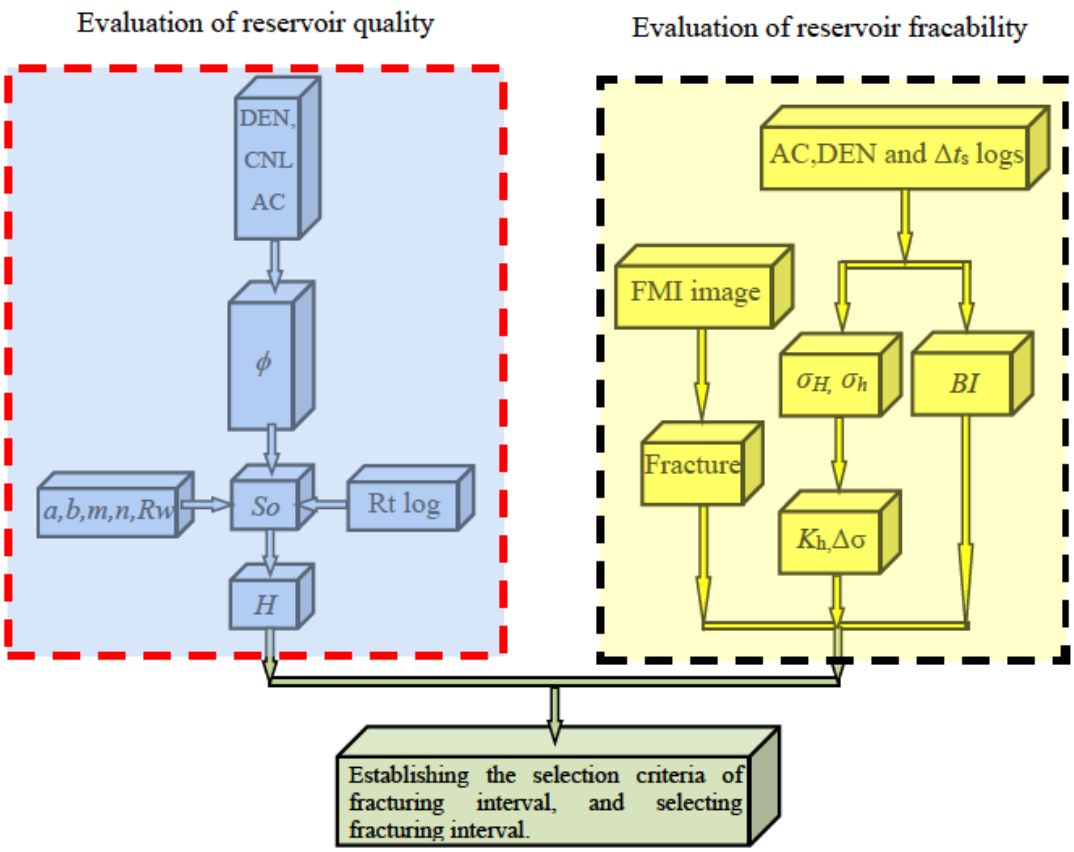


Figure 2: Workflow

the difference coefficient of horizontal stress is obtained. Thirdly, the brittle index is calculated combined with consideration for the contribution of both the volume of brittle minerals (quartz, calcite) and the sensitive elastic parameter of the mineral to rock brittleness.

(C) Select fracturing interval

By using the evaluation parameters of reservoir quality and reservoir fracability, the selection criteria of fracturing interval is establishing, and the fracturing intervals are selected.

3.2 Materials

The Cretaceous Qingshankou Formation is mainly composed of gray-black mudstone (often silty) and siltstones, which are irregularly interbedded by calcareous siltstones (Figure 3). The succession was deposited in the marginal-marine, deltaic environment [14]. The the Qing I Member of Qingshankou Formation represents the sedimentary infill of underwater channel and estuary dam facies, which were deposited on the delta front during the rising of sea level and gradual expansion of the delta lake. The mudstones, which are dominated among the Qing I Member, are continuously distributed in most areas of the region; they become thinner from the southwest to the northeast. The oil-reservoir sand bodies are divided into three sand groups. First group is formed by a sheet sands of the delta front and shallow lake muds. The III and IV groups are built mainly by estuary dam facies. The sandstones exhibit a band geometry and their thickness gradually decreases toward the northeast. In particular, the sandstones of III and IV groups are better distributed over the entire region and their inner connection is better developed. The summarized thickness of sandstones is generally 20-35 m, but it can be more than 50 m. The thickness of the reservoir rocks is generally 2-6 m.

The core description data show that the lithology of the Qing-1 Member is mainly mudstone, silty mudstone, and siltstone. The reservoir is mainly composed of fine sandstones and siltstones. The core photos from QD43-9 well (Figure 4) document the dominated lithology of reservoir rocks. The interval 2395.06 m is a gray oil trail siltstone.

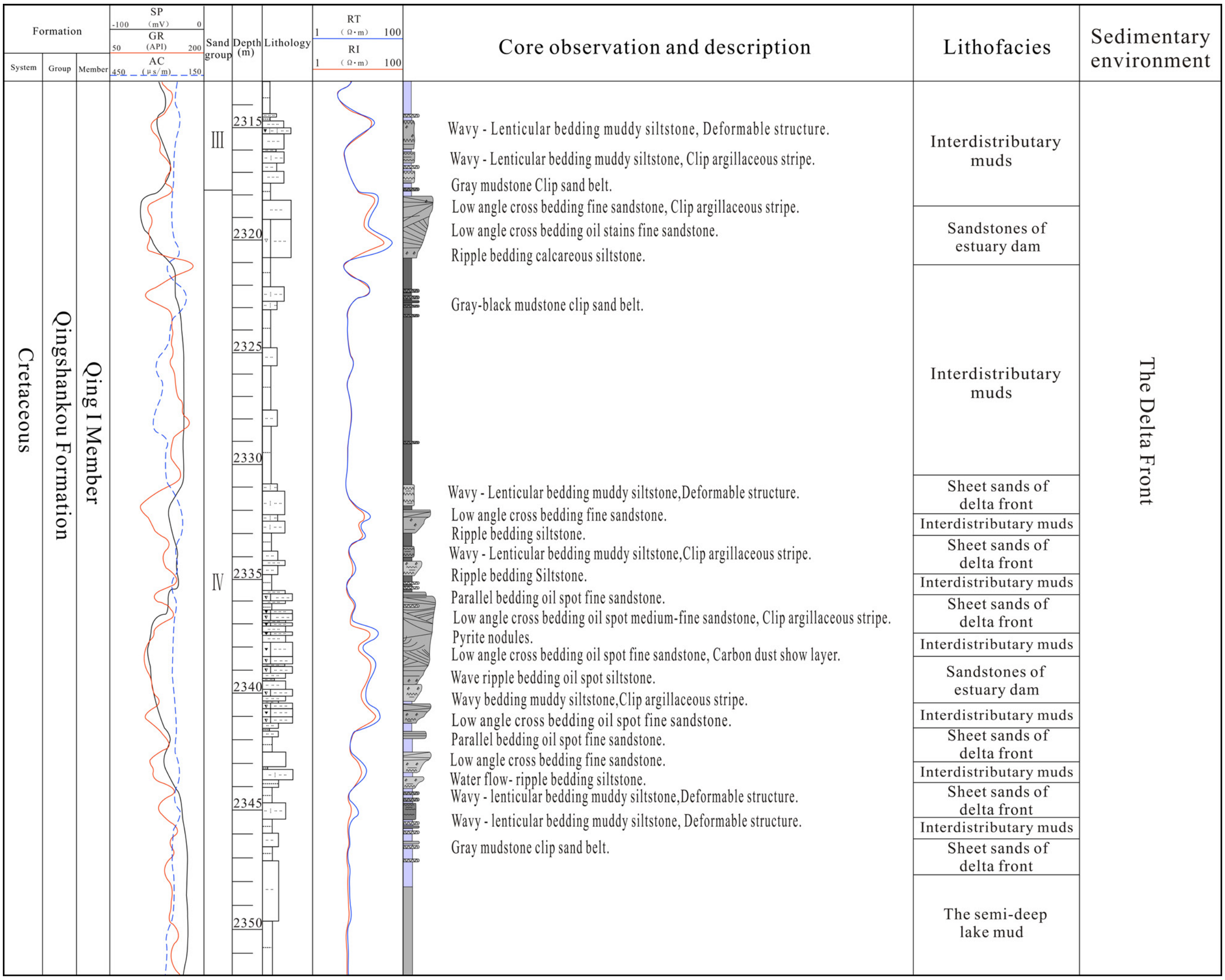


Figure 3: Simplified lithology of the Qing I Member of Qingshankou Formation of Daqingzijing Oilfield in Songliao basin [15]

(a) (b)

Figure 4: (a) Gray oil trail siltstone; QD43-9 well, depth 2395.06m; (b) Gray-white siltstone with gray-black mudstone drapes (heteroliths); QD43-9 well, depth 2395.97m

Table 1: Data of petrographic analysis of the Qing I Member

Well number	Number of samples	quartz %	Calcite %	Plagioclase %	Potassium feldspar %	Clay minerals %
H57	6	13.6-17.3	4-9.8	58.8-73.8	7.4-11.8	1.6-4.6
H116	5	11.8-20.7	3.3-3.3	57.1-64.5	13.9-17.3	3-9.8
H71	5	15.6-19.8	0-1.1	63.6-72	8.1-11	2.2-8.1
H83	8	11.3-14.9	3.3-3.3	63.5-70.9	13.3-17.9	2.1-6.7
H89	7	12.8-16.6	1.7-6.1	58.6-69.7	12.6-17.7	1.6-4.6
H123	8	11.3-17.9	1.5-4.9	58.8-70.7	12-19.1	1.8-6.8
QD43-9	11	12-19.8	3.9-5.7	52.2-71.9	7.6-17.5	3.1-13.9
Average value		15.2	4.1	63.1	13.5	4.1

The interval 2395.97 m is a gray-white siltstone with gray-black mudstone strips. The grinding circle is sub-circular.

The petrographic analysis of 50 samples of rocks (Table 1) shows that the sandstones of the Qing I Member are mainly composed of feldspars, quartz and calcite. The quartz constitutes only 11.3-20.7%, with an average of 15.2%, while plagioclase content is 52.2-73.8%, with an average of 63.1%. Relatively high content of potassium feldspars was observed in the samples - from 7.4 to 17.9%, with an average of 13.5%. The calcite is below 9.8%, with an average of 4.1%.

According to the statistical analysis of the petrophysical data of 50 samples in the Qing-1 Member of the research area, the porosity distribution is 3.6-17.4%, with an average of 12.1% and a permeability of 0.03mD-6.13 mD, with an average of 0.26mD.

3.3 Methodology

3.3.1 Evaluation of reservoir quality

The quality of reservoir is the first consideration in the selection of fracturing interval. A high-quality tight reservoir should have the good physical properties, the high oil saturation and the thick reservoir [16]. On this basis, the porosity, oil saturation and effective thickness of the tight reservoir in the study area are evaluated by making full use of core analysis and logging data.

3.3.1.1 Porosity

Reservoir porosity is a basic parameter that reflects the reservoir quality. The precision of porosity calculations is directly related to the accuracy of oil saturation. Studies have shown that there are many ways to calculate porosity based on logging. Density, acoustic time difference, compensated neutron and nuclear magnetic resonance (NMR) logging can be used to calculate reservoir porosity [17]. Despite the unique advantages of NMR logging in porosity calculation, the number of NMR logs is limited in the study area. Thus, conventional logging data are used to calculate the porosity of a tight reservoir.

Feldspar, quartz and calcite coexist in the tight oil reservoir of the study area, with large variation in the content. The mixed matrix value greatly changes, leading to uncontrolled precision of the porosity calculation with the conventional single porosity method. The tight oil reservoir includes matrix, clay and pores. However, pores contain not only oil and gas but also formation water. For this reason, the following log response equations of the variable matrix method are obtained based on the rock volume physical model for tight oil reservoirs as shown in Figure 5 using neutron, density and sonic logging:

$$\rho_b = (1 - V_{sh} - \varphi)\,\rho_{ma} + V_{sh}\rho_{sh} + \varphi\,[S_w\rho_w + (1 - S_w)\,\rho_h] \tag{1}$$

$$\Phi_N = (1 - V_{sh} - \varphi)\,\Phi_{Nma} + V_{sh}\Phi_{Nsh} + \varphi\,[S_w\Phi_{Nw} + (1 - S_w)\,\Phi_{Nh}] \tag{2}$$

$$\Delta t = (1 - V_{sh} - \varphi)\,\Delta t_{ma} + V_{sh}\Delta t_{sh} + \varphi\,[S_w\Delta t_w + (1 - S_w)\,\Delta t_h] \tag{3}$$

where ρ_b, ρ_{ma}, ρ_{sh}, ρ_w and ρ_h refer to the formation bulk density, matrix density, clay density, formation water density and oil density in g/cm^3, respectively; Φ_N, Φ_{Nma}, Φ_{Nsh}, Φ_{Nw} and Φ_{Nh} refer to the compensated neutrons of formation, matrix, clay, formation water and oil in %, respectively; Δt, Δt_{ma}, Δt_{sh}, Δt_w and Δt_h refer to the interval transit-time of formation, matrix, clay, formation water and oil in $\mu s/m$, respectively; V_{sh} refers to the clay content of formation in %; φ refers to the formation porosity in %; and S_w refers to the water saturation of formation in %.

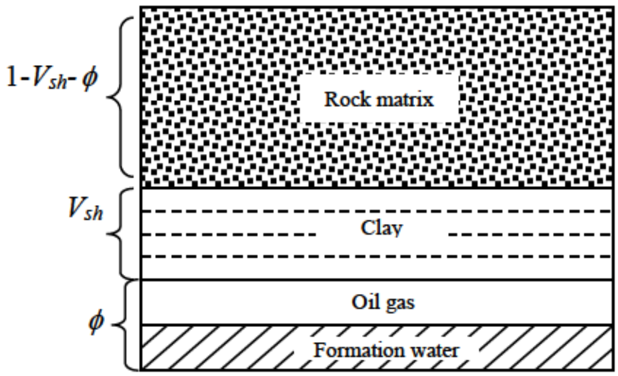


Figure 5: Rock volume physical logging model for tight oil reservoir.

The matrixes of the tight oil reservoir rocks in the study area consist of quartz, feldspar and calcite. The matrix values in Equations (1) to (3) are the weighted volume content of several mineral matrix values:

$$\rho_{ma} = v_{quartz} \cdot \rho_{quartz} + v_{feldspar} \cdot \rho_{feldspar} + v_{calcite} \cdot \rho_{calcite} \tag{4}$$

$$\Phi_{ma} = v_{quartz} \cdot \Phi_{quartz} + v_{feldspar} \cdot \Phi_{feldspar} + v_{calcite} \cdot \Phi_{calcite} \tag{5}$$

$$\Delta t_{ma} = v_{quartz} \cdot \Delta t_{quartz} + v_{feldspar} \cdot \Delta t_{feldspar} + v_{calcite} \cdot \Delta t_{calcite} \tag{6}$$

where v_{quartz}, $v_{feldspar}$ and $v_{calcite}$ refer to the contents of quartz, feldspar, and calcite in %.

3.3.1.2 Oil saturation

Tight reservoirs have complex pore structures. It is difficult to calculate oil saturation by using the traditional Archie equation. In the oil saturation evaluation of tight oil reservoir, the simplified Simandoux equation is often used:

$$\frac{1}{R_t} = \frac{\varphi^m S_w^n}{aR_w(1 - V_{sh})} + \frac{V_{sh} S_w}{R_{sh}} \tag{7}$$

where R_t is the resistivity log value of reservoir, in $\Omega \cdot m$; R_w is the resistivity of formation water, $\Omega \cdot m$; R_{sh} is the resistivity of pure clay, in $\Omega \cdot m$; mn are the cementation index and saturation index of reservoir, dimensionless; a is the lithological index, dimensionless; and the other parameters have the same physical meanings as above.

The tight oil reservoir has complex pore structures. In a set of reservoirs, the precision of oil saturation calculated by using constant mn values is not high. With full consideration for the influence of the formation water, pore structure and clay content on reservoir resistivity, to eliminate the influence of pore structure on resistivity and highlight the contribution of fluid to resistivity, this study uses m and n values changing with the depth points. The calculation of variables m and n, as shown in Equations (8) and (9), is established with the formation water resistivity, porosity, permeability, clay content and rock-electric experiment data of the study area.

$$m = 1.704 - 0.094 \cdot R_w + 0.38 \cdot \lg\left(\frac{K}{\varphi}\right)^{\frac{1}{2}} - 0.032 \cdot V_{sh} \tag{8}$$

$$n = 2.11 - 0.148 \cdot R_w - 0.304 \cdot \lg\left(\frac{K}{\varphi}\right)^{\frac{1}{2}} - 0.039 \cdot V_{sh} \tag{9}$$

where K refers to permeability in 10^{-3} μm^2. Other parameters have the same physical meanings as above.

3.3.1.3 Effective thickness of reservoirs

The cross-plot as shown in Figure 6 is drawn with the production data and the effective thickness of a single layer. According to the economic and technical conditions of Jilin oilfield, the reservoir with a well test capacity of more than 1 m^3/d is deemed to achieve an industrial oil flow. As shown in the figure, the lower limit of effective thickness in the study area is 1 m.

It is also difficult to obtain higher production, because tight oil reservoirs have small porespace for oil storage,

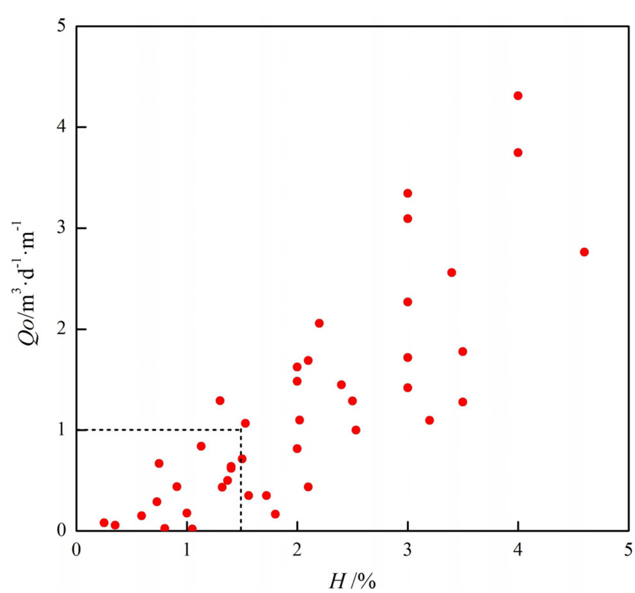


Figure 6: The diagram of relation of the effective thickness and the daily well testing production.

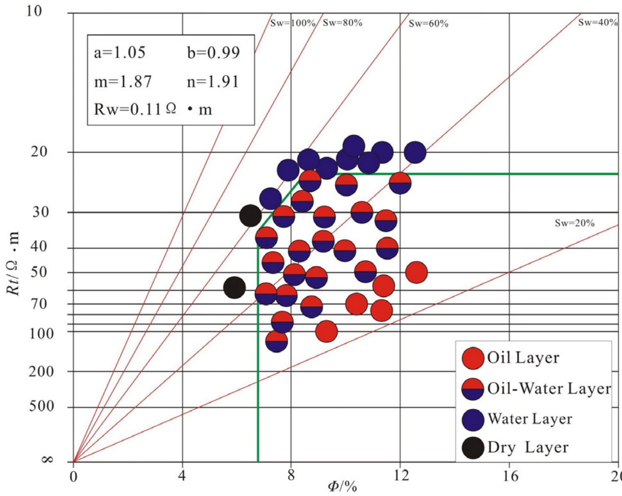


Figure 7: Crossplot of porosity –resistivity in the study area.

even if the reservoir has a large thickness. For this reason, a high capacity is achieved in production practices. Therefore, it is often used by multilayers-commingled fracturing to achieve high yield in the actual development of tight oil. This study defines the effective thickness as the sum of the effective thicknesses of multiple sets of oil reservoirs that can be connected during multilayers-commingled fracturing. Thus, during dividing the effective thickness of tight oil reservoirs, the cumulative thickness of each layer is used as the basis for the optimal selection of the fracturing interval.

Data determining the benchmark of effective thickness include porosity, oil saturation and resistivity of oil reservoir. The crossplot of the porosity – resistivity in the study area shown in Figure 7. In Figure 7, rock-electric parameters are calculate using Equations (8) and (9) with the formation water resistivity, porosity, permeability and clay content of the study area. The parameters of a, b, m and n are 1.05., 0.99, 1.87, 1.91, respectively. It can be seen in the figure that the lower limits of porosity, oil saturation and resistivity of the the Qing I Member of Qingshankou Formation are 7.6%, 42% and 23 $\Omega \cdot m$, respectively. The effective thickness of the study area can be divided according to the standard of lower limit.

3.3.2 Evaluation of reservoir fracability

The fractures, the brittleness and the coefficient of stress difference are three factors to evaluate reservoir fracability. In this study, the parameter of interlayer stress difference is introduced to evaluate whether it is possible to press into several sets of oil-bearing intervals.

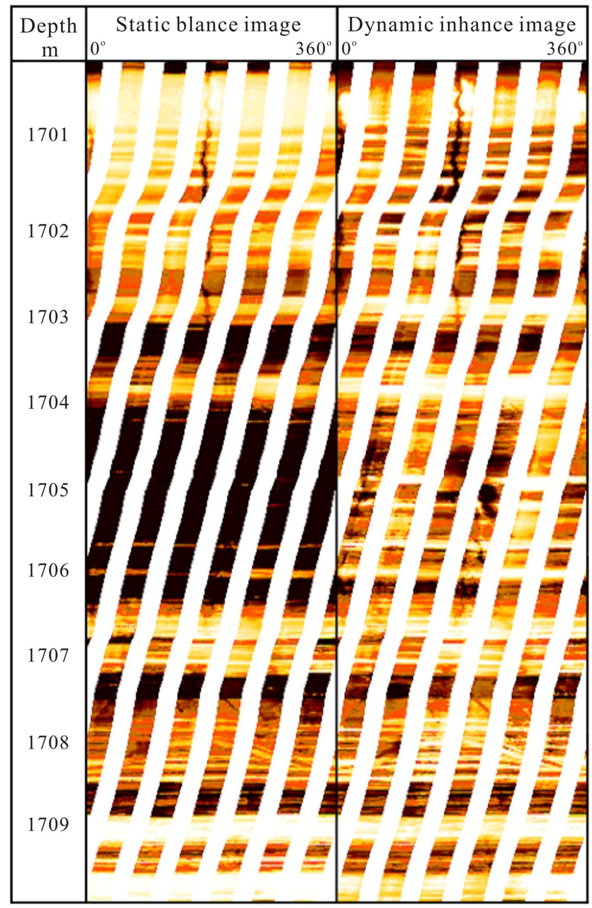


Figure 8: Imaging logging of well H43-9 in the Qing I Member of Qingshankou formation.

3.3.2.1 Natural fracture

Fractures improve the seepage characteristic of reservoirs, and provide a better seepage channel for oil production. Since natural fractures provide conditions for injection of fracturing fluid at a high rate, the more developed natural fractures are, the better the fracability of tight reservoir will be [15].

Static electric imaging images of well sections between 1700 ~ 1703 and 1706.6 ~ 1707.3m show bright. As shown in FMI image (Figure 8), a brighter static electro-imaging for intervals of 1700-1703 and 1706.6-1707.3 m indicates that the formation resistivity is high, and the lithology is tight sandstone. A group of high-angle fractures develops in the interval, but the fractures have small widths, being locally filled and semi-filled. Core description and imaging logging of several wells in the study area show that fractures in the the Qing I Member of Qingshankou Formation develop poorly, with only microfracture developing. However, with the influence of tectonic movement, in particular, the better development of fractures are seen at locations near the fault. Nevertheless, microfractures in the study area, even closed fractures, may improve the rock mechanics of reservoirs and reduce the fracturing pressure. It will be easier for fracturing fluid to flow along the natural microfractures and further develop larger induced fractures.

The bright colors on the imaging logging images indicates high resistivity, and the opposite - dark colors on the imaging logging images indicates low resistivity. Since the resistivity of the mud is much lower than that of the formation, when the formation contains fractures, the imaging logging images show dark colors because of the mud filling fractures.

3.3.2.2 Coefficient of stress difference

Studies have shown that the smaller the stress difference of tight reservoir is, the more favorable it will be for development of networked fractures [5]. During reservoir fracturing, new fractures occur while fracturing fluid flows into a microfracture. If the stress difference is small, the fractures will extend in several directions. Many tensional and shearing fractures will be generated to form a relatively developed flow network and achieve volume fracturing. On the contrary, there will be only several main fractures, which is insufficient for volume fracturing.

The co-existence of natural fractures, brittleness and small stress difference is an essential geological condition under which reservoirs with extremely tight permeability achieve high capacity. The stress difference of tight reservoir is a key factor in the successful achievement of volume fracturing. The index for describing the difference of stress is the coefficient of stress difference. Generally, the coefficient of stress difference is calculated using Equation (10) [17]:

$$K_{\mathrm{h}} = \frac{\sigma_H - \sigma_h}{\sigma_h} \tag{10}$$

where

$$\sigma_H = \frac{\mu}{1-\mu}(\sigma_v - \alpha P_p) + \frac{E}{1-\mu^2}\varepsilon_H + \frac{E\cdot\mu}{1-\mu^2}\varepsilon_h + \alpha P_p$$

$$\sigma_h = \frac{\mu}{1-\mu}(\sigma_v - \alpha P_p) + \frac{E}{1-\mu^2}\varepsilon_h + \frac{E\cdot\mu}{1-\mu^2}\varepsilon_H + \alpha P_p$$

$$\sigma_v = 0.00980665 \times (\rho_o \times H_o + \int_{H_0}^{H} \rho_b dH)$$

$$P_p = \sigma_v - 145.31 \times \left(\frac{\frac{1}{\Delta t_{ma}} - \frac{1}{\Delta t}}{A}\right)^{\frac{1}{B}}$$

where K_{h} refers to the coefficient of stress difference, dimensionless; σ_H refers to the maximum main stress, MPa; σ_h refers to the minimum main stress, MPa; σ_v refers to the vertical stress, MPa; α refers to the Biot coefficient, dimensionless; P_p refers to the formation pore pressure, MPa; ε_H refers to the tectonic stress coefficient along the maximum horizontal stress, dimensionless; ε_h refers to the tectonic stress coefficient along the minimum horizontal stress, dimensionless; ρ_o refers to the formation average density, g/cm^3; H_o refers to the initial depth of density logging, m; H refers to the depth of the calculated point, m; Δt_{ma} refers to the scoustic time difference of tight reservoir's matrix, μs/ft; A and B denote the regional coefficients, dimensionless; and the other parameters have the same physical meanings as above.

The coefficient of stress difference is relatively small, which can produce a large number of tensile and shear fractures, and build a relatively developed seepage network to achieve the effect of volume fracturing. On the contrary, there will be only several main fractures, which is far insufficient for volume fracturing.

3.3.2.3 Stress difference between tight reservoir and its surrounding rock

There are obvious differences in the mechanical properties between tight reservoirs and surrounding rocks, which can lead to the vertical principal stress field in the tight reservoir. The larger the elastic modulus difference between tight reservoir and its surrounding rock is, the larger the minimum principal stress difference is, the hydraulic fracture are more easy to be contained in tight reservoirs [18].

The size and direction of stress on surrounding rocks control the initiation and expansion direction of hydraulic fracture. They also play a key role in expansion of fractures. In certain stress field conditions, as long as the elastic modulus difference between tight reservoirs and surrounding rocks is small, and the spread pressure difference is also small, it will be easy for induced fractures to reach the neighboring oil-bearing formation. This indicates that the stress difference between tight reservoir and their surrounding rock has a great influence on expansion of induced fractures.

The stress difference between tight reservoir and their surrounding rocks can be obtained based on the calculated stress of tight reservoir and their surrounding rocks using logging data.

$$\Delta\sigma = \sigma_{\mathrm{s}} - \sigma_{\mathrm{c}} \tag{11}$$

where σ_{s}, $\sigma_{\mathrm{c}} = \frac{\mu}{1-\mu}(\sigma_v - \alpha P_p) + \beta_1(\sigma_v - \alpha P_p) + \alpha P_p$
where $\Delta\sigma$ refers to the stress difference between tight reservoir and their surrounding rocks, MPa; σ_{s} refers to the min-

imum stress of tight reservoir' surrounding rocks, MPa; σ_c refers to the minimum stress of tight reservoir, MPa.

3.3.2.4 Evaluation of rock brittleness

Rock brittleness is the plastic property before rock failure, viz. the nature of rock failure facilitated in the presence of external forces [19]. Brittleness relies on the content of quartz, feldspar and calcite in the reservoir. If a reservoir has more clay, it will have high elasticity, and it is rather difficult to fracture [19]. For this reason, the higher the brittleness of a tight reservoir is, the better the fracability will be.

The brittle index is usually the ratio of tensile strength and compressive strength of rocks. The higher the index, the easier the reservoir fracturing, and the easier it is to form network fractures [21]. Therefore, the brittleness of rock is one of the important factors to consider in the fracturing design of tight reservoirs.

Among existing evaluation methods of the brittleness index, the most common is based on lab analysis and the mechanical data of the tight reservoir. For example, the Young's modulus and Poisson's ratio obtained by the stress-strain test evaluate the brittle index of tight reservoir. In practical production, the Young's modulus and Poisson's ratio are often calculated by logging data [22]. Another commonly used method calculates the brittleness index according to the content of brittle minerals in sandstone (quartz and calcite minerals) using logging data.

Studies show that rock brittleness depends on the composition of brittle minerals. In sandstone reservoirs, the mineral with the highest brittleness is quartz, followed by calcite and feldspar. The reservoir minerals in the study area are mainly plagioclase, followed by quartz and calcite. The contribution of plagioclase, quartz and calcite to brittleness is different. Thus, the Poisson's ratio of mineral is used as its weight. A model for calculating brittleness index, which consider the volume content of brittle minerals and their contribution to rock brittleness is expressed as follows:

$$BI = \frac{\frac{1}{\mu_{quartz}} \cdot V_{quartz} + \frac{1}{\mu_{calcite}} \cdot V_{calcite} + \frac{1}{\mu_{feldspar}} \cdot V_{feldspar}}{B} \times 100 \tag{12}$$

where

$$B = \frac{1}{\mu_{quartz}} \cdot V_{quartz} + \frac{1}{\mu_{calcite}} \cdot V_{calcite} + \frac{1}{\mu_{feldspar}} \cdot V_{feldspar} + \frac{1}{\mu_{clay}} \cdot V_{clay}$$

where BI refers to the brittleness index of tight reservoir, %; μ_{quartz}, $\mu_{calcite}$ and μ_{clay} refer to the Poisson's ratio of quartz, calcite and clay, respectively, dimensionless; and V_{quartz}, $V_{calcite}$ and V_{clay} refer to the content of quartz, calcite and clay, respectively, %.

3.3.3 Criteria for the optimal selection of the fracturing interval

The tight oil reservoir has poor permeability, which results in the absence of natural productivity. Fracturing is the only technological measures of oil productivity. Accordingly, it is very important to optimize fracturing interval on a scientific and reasonable basis.

From the foregoing analysis, the high reservoir quality is a key factor in optimally selecting the fracturing interval. Thus, the porosity, the oil saturation and the effective pay thickness are used as three reservoir parameters for the optimal selection of fracturing interval.

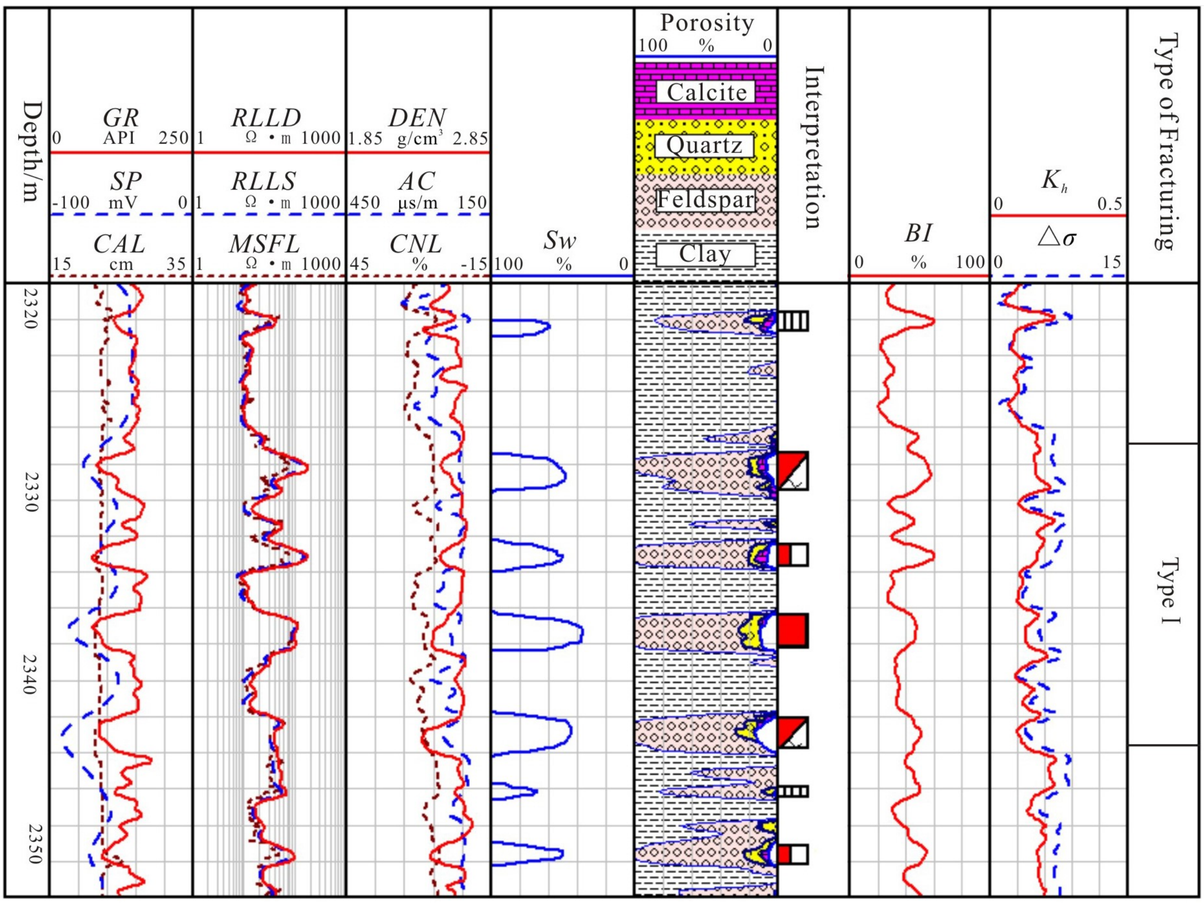
Studies have shown that the microfractures in the tight reservoir contribute to fracturing and oil seepage. Due to the small coefficient of stress difference in tight reservoirs, it is easy to form complex fractures. When the minimum stress difference between the tight reservoir and the surrounding rock is low, it is easier to fracture the tight reservoir and reach the neighboring oil-bearing reservoir. The higher the brittleness index, the more the tight reservoir is easy to be fractured. For this purpose, the development of a microfracture in the tight reservoir, the coefficient of stress difference, the stress difference between the tight reservoir and the surrounding rock and brittleness index are taken as four fracturing quality parameters for optimal fracturing.

Based on the above method, seven evaluation parameters for the optimal selection of the fracturing interval in the tight reservoir were evaluated. And after systematically comparing the actual fracturing effect and production data, the criteria for the optimal selection of the fracturing interval of the tight reservoir as shown in Table 2 are summarized.

As shown in Table 2, the criteria for the optimal selection of the fracturing interval of the tight reservoir are classified into three categories in this study. Type I means that the reservoir quality is good, the fracability is high, which it is the preferred optimal interval. Type II means that it is a replacement interval for future development with medium reservoir quality and reservoir fracability. Type III indicates that the reservoir quality is poor, and it is difficult to successfully fracturing.

Table 2: Criteria for the optimal selection of the fracturing interval of tight reservoir.

Type of fracturing interval	Porosity POR	Oil saturation So	Effective thickness H	Development of microfracture in the reservoir	Coefficient of horizontal main stress difference K_h	Stress difference between tight reservoir and surrounding rock $\Delta\sigma$	Brittleness index I_B
Type I	>10	>60	>5	Developed	<0.25	<2	>50
Type II	7<POR<10	50<So<60	3<H<5	Relatively developed	$0.25<K_h<0.35$	$2<\Delta\sigma<5$	$40<I_B<50$
Type III	5<POR<7	40<So<50	1<H<3	Not developed	>0.35	>5	$30<I_B<40$



The red in the "Interpretation" column mean oil layer, the white-red squares mean poor oil layer, the wave symbol-red squares mean oil-water layer, and the squares with black lines mean dry layer.

Figure 9: Result of the fracturing interval optimally selected for well H43-9.

4 Case study

Based on the above methods, the fracturing interval for many wells in the research area were selected using logging data. Figure 9 illustrates the selected result of the fracturing interval for Well H43-9. As shown in the figure, the interval 2319.6-2320.6 m of the well is interpreted to be a dry reservoir, and intervals 2332.4-2333.8 m and 2349.0-2350.2 m are interpreted to be poor reservoirs. The interval 2336.2-2338.4 m is interpreted to be an oil reservoir. The intervals 2326.4-2329.8 and 2341.8-2344.2 m are interpreted to be oil-water reservoirs. Among them, intervals 2326.4-2329.8, 2336.2-2338.4 and 2341.8-2344.2 m are major oil-bearing intervals. The reservoir porosity, oil saturation and accumulative effective thickness of the three oil-bearing intervals are 10.1%, 55.6% and 8 m. It indicates that the three oil-bearing intervals have the high reservoir quality.

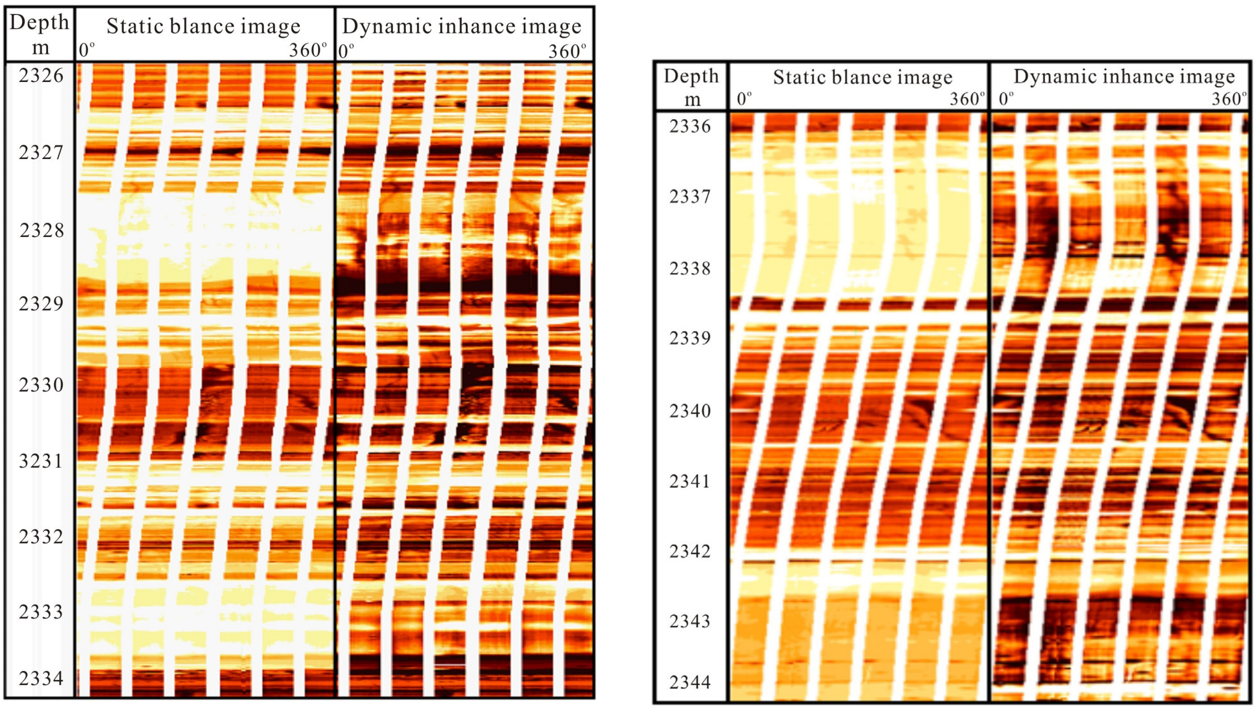


Figure 10: Imaging logging of reservoir interval of well H43-9.

The vertical microfractures of the three sets of tight oil reservoirs are relatively developed (Figure 10), providing natural conditions for the entry of fracturing fluid into the fractures and the further development of complex fractures. In terms of the geostress and brittleness index subject to the logging interpretation, the three sets of oil-bearing intervals have a low coefficient of the minimum horizontal main stress difference and a high brittleness index. Therefore, it would be easy to develop complex fracture systems upon fracturing. Despite the fact that the three sets of oil-bearing intervals have a thin clay interbed, it would be difficult to reach the other two sets of oil-bearing reservoirs if one of them is fractured because there is a large stress difference between the reservoir and the surrounding rock. Commingled fracturing of the several sets of neighboring tight oil reservoir series plays a key role in achieving a high yield.

The three sets of oil-bearing intervals are grouped in Type I for the evaluation of the reservoir quality, reservoir fracability and based on the criteria for the optimal selection of the fracturing interval of the tight reservoir included in Table 1. Separated-layer fracturing of the interval was commenced on December 5, 2017. The oil and water production was 12.4 t and 4.72 m^3, respectively, in the well testing, indicating that it was an oil-water reservoir. The result of the optimal selection of the fracturing interval evaluated in this study complies with the actual production. In addition, accurate optimal interval of the fracturing interval plays a key role in the improved hydrocarbon productivity.

5 Discuss

In the development of conventional oil and gas fields, we generally select the fracturing intervals based on reservoir evaluation results or experience. That is to say, reservoirs with good petrophysical properties, high oil saturation, and large effective thickness are often used as fracturing intervals [19]. Currently, during the development of tight oils, the fracturing interval is generally optimized based on reservoir quality and reservoir brittleness [20]. However, it cannot guarantee good production after fracturing.

As can be seen from Figure 9, the high productivity of the well is that the three sets of tight oil reservoirs studied have good petrophysical properties, high oil saturation and large cumulative thickness. The three sets of tight oil reservoirs are located near the source rocks, and the reservoirs have higher oil-charging levels; the upper and lower reservoir intervals are in direct contact with the effective source rocks, which helps to form a good reservoir matching relationship. Small interlayer stress difference coefficient, large brittleness index, and the well development of microfractures and bedding in the reservoir lead to the formation of complex fracture networks in reservoirs. Although the difference in interlayer stress is large, commingled fracturing of the three sets of tight oil reservoirs was used in fracturing construction.

This method not only considers the reservoir quality and the brittleness index of the reservoir, but also fully recognizes the influence of stress difference, stress difference coefficient and natural fracture development characteristics on the fracturing effect. Accordingly, the four fracturing ability parameters are the stress difference coefficient, the brittleness index, the degree of fracture development and the stress difference between the tight reservoir and its surrounding rock. Three reservoir quality parameters, namely porosity, oil saturation and effective thickness, were used to determine the criteria for fracturing interval optimization. This method is completely different from the existing methods. Moreover, the factors considered by this method are much more comprehensive, and the practical application shows that the preferred fracturing intervals have better production effects.

6 Conclusions

1. A single-layer of tight oil reservoir can be obtaining only low yield because of its small porosity and thin thickness. Several sets of tight oil reservoirs with high reservoir quality are a key factor for optimally selecting the fracturing interval.
2. The coefficient of stress difference, brittleness index and development degree of fractures in tight oil reservoirs have a strong influence on fracability. The smaller the coefficient of stress difference, the higher the brittle index and the more the fractures develop, then the easier it is to form complex networked fractures. When the stress difference between several sets of tight oil reservoirs and their mudstone interlayers is smaller, it is easier to communicate the several sets of oil-bearing reservoirs during fracturing. In order to obtain higher oil production, it is necessary to fracture several sets of oil-bearing reservoirs.
3. This paper provides a technical process for optimally selecting the fracturing interval of a tight oil reservoir in terms of logging. This technical process not only considers the reservoir quality, it also uses the reservoir fracability, which provides reliable logging technique support for optimally selecting the fracturing interval of tight oil reservoir.

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References

[1] Zou C. N., Zhai G. M., Zhang G. Y, Wang H. J., Zhang G. S., Li J. Z., Wang Z. M., Wen Z. X,. Ma F., Liang Y. B., Yang Z. and Liang K. Formation, distribution, potential and prediction of global conventional and unconventional hydrocarbon resources.(2015),Petroleum Exploration and Development (42),13-25 (in Chinese)

[2] Rafie M., Almubarak T., Said R., Nugraha I., Al-Mutairi K. M., Al-Hajri M., Soriano E., Pacheco E. and Lucado J. Engineering approach to achieve the first successful multistage acid frac of a tight oil reservoir producer in Saudi Arabia. (2015), Society of Petroleum Engineers- SPE Middle East Oil and Gas Show and Conference.

[3] Behmanesh H., Hamdi H. and Clarkson C.R. Analysis of transient linear flow associated with hydraulically-fractured tight oil wells exhibiting multi-phase flow. (2015), Society of Petroleum Engineers - SPE Middle East Unconventional Resources Conference and Exhibition.

[4] Bai B., Salehi S., Nygaard R. and Aladasani A. Optimizing the development of tight oil formations. (2014), Society of Petroleum Engineers- SPE European Unconventional Resources Conference and Exhibition.

[5] Clarkson C.R. and Qanbari F. An approximate semianalytical multiphase forecasting method for multifractured tight light-oil wells with complex fracture geometry. (2015), Journal of Canadian Petroleum Technology (54),489-508

[6] Carpenter C., Hegazy G.M., Salem A.M., A new strategy explores tight oil/gas reservoirs: Fit-for-purpose acid fracturing. (2013),Journal of Petroleum Technology, 65(6),100-103

[7] Clarkson, C.R., Qanbari, F.,Williams-Kovacs, J.D., Semi-analytical model for matching flowback and early-time production of multi-fractured horizontal tight oil wells. (2016), Journal of Unconventional Oil and Gas Resources, 15(5), p 134-145

[8] Velasco R., Panja P., Pathak M., Deo M., Analysis of North-American Tight oil production. (2018), AIChE Journal, 64(4), 1479-1484

[9] Du J.H., Liu H., Ma D.S., Fu J.H., Wang Y.H. and Zhou T.Y. Discussion on effective development techniques for continental tight oil in China.(2014), Petroleum Exploration and Development (41),198-205 (in Chinese)

[10] Saputelli L., Chacon A. and Lopez C. Optimum well completion strategies in tight oil reservoirs. (2014), Offshore Technology Conference..

[11] Lin M., Chen S., Chen Z. and Xu J. Fractured Reservoir Modeling: Effects of Hydraulic Fracture Geometries in Tight Oil Reservoirs. (2014), Society of Petroleum Engineers - European Unconventional Resources Conference and Exhibition.

[12] Hu W.S.,Cai C.F.,Wu Z.Y., Li J.M.1998. Structural style and its relation to hydrocarbon exploration in the Songliao basin, northeast China. Marine and Petroleum Geology, 15, 41-55.

[13] Liu R., Liu, Z.J., Sun P.C. 2017. Shale gas accumulation potential of the Upper Cretaceous Qingshankou Formation in the southeast Songliao Basin, NE China. Marine and Petroleum Geology, 86, 547-562.

[14] Wei Z S, Song X M, Tang Z X, Chu X and Yang G Sedimentary facies and lithologic oil pools of the upper cretaceous qingshankou formation in Daqingzijing area, Changling Sag, southern Songliao basin. (2007), Petroleum Exploration and Development (34),28-33 (in Chinese)

[15] Liu Z.D., Shi Y.J., Zhou J.Y., Wang C.S, Zhang P. and Ma T.H. Selecting sweet spots for the exploitation of tight oil reservoirs from logs: case studies. (2019), Exploration Geophysics(50), 352-364

[16] Zhao H.W., Ning Z.F., Zhao T.Y., Yu L., Zhang R., Dou X.J. and Hou T.F. Geological and petrophysical characterization of tight oil reservoirs: a case study from upper triassic Yanchang formation, Ordos Basin in North China. (2015), Society of Petroleum Engineers- SPE Asia Pacific Unconventional Resources Conference and Exhibition.

[17] Ghanizadeh A., Clarkson C.R., Aquino S., Ardakani O.H. and Sanei H. Petrophysical and geomechanical characteristics of Canadian tight oil and liquid rich gas reservoirs: II. Geomechanical Property Estimation. (2015), Fuel (53),682-691

[18] Jimenez B.L., Yu G., Aguilera R. and Settari A. Calibration of well logs with mini-frac data for estimating the minimum horizontal stress in the tight-gas monteith formation of the western Canada sedimentary basin: A Case Study. (2015), SPE Production and Operations (30),110-120

[19] Song L. and Hareland G. Minimum horizontal stress profile from logging data for montney formation of north east British Columbia. (2012), Society of Petroleum Engineers - SPE Canadian Unconventional Resources Conference.

[20] Saeidi O., Torabi S.R., Ataei M. and Hoseinie S.H. Prediction of rock fracture toughness modes I and II utilising brittleness indexes. (2013), International Journal of Mining and Mineral Engineering (4),163-173

[21] Schlosser D.J., Johe M., Humphreys T., Lundberg C. and McNichol J.L. Evolution of completion techniques in the lower Shaunavon tight oil play in southwestern Saskatchewan. (2015), Society of Petroleum Engineers - SPE Hydraulic Fracturing Technology Conference.

[22] Fan Z.Y., Lin C.Y., Wang T.X. and Ge X.M. Logging optimization modeling on brittleness index of tight formation rocks. (2015), Acta Petrolei Sinica (36),1411-1420 (in Chinese)