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Research Article

Damage Mechanism of Oil-Based Drilling Fluid Flow in Seepage Channels for Fractured Tight Sandstone Gas Reservoirs

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Oil-based drilling fluids (OBDFs) have a strong wellbore stabilization effect, but little attention has been paid to the formation damage caused by oil-based drilling fluids based on traditional knowledge, which is a problem that must be solved prior to the application of oil-based drilling fluid. For ultradeep fractured tight sandstone gas reservoirs, the reservoir damage caused by oil-based drilling fluids is worthy of additional research. In this paper, the potential damage factors of oil-based drilling fluids and fractured tight sandstone formations are analyzed theoretically and experimentally. The damage mechanism of oil-based drilling fluids for fractured tight sandstone gas reservoirs is analyzed based on the characteristics of multiphase fluids in seepage channels, the physical and chemical changes of rocks, and the rheological stability of oil-based drilling fluids. Based on the damage mechanism of oil-based drilling fluids, the key problems that must be solved during the damage control of oil-based drilling fluids are analyzed, a detailed description of formation damage characteristics is made, and how to accurately and rapidly form plugging zones is addressed. This research on damage control can provide a reference for solving the damage problems caused by oil-based drilling fluids in fractured tight sandstone gas reservoirs.

1. Introduction

Fractured tight sandstone formations have special engineering geological characteristics and are vulnerable to damage caused by the invasion of foreign fluids during drilling and completion. OBDF is more stable than water-based drilling fluids (WBDFs), and OBDF has been widely used in fractured tight sandstone formation drilling as the cost of OBDF has approached that of WBDF in recent years [1]. Traditionally, OBDF has protected reservoirs more effectively than WBDF [2], because the continuous phase of OBDF is its oil phase and its filtration capacity is low, which reduces the hydration of clay minerals and the invasion of filtrate into the formation. However, many years of applied practice show that OBDF can also cause formation damage and this damage is more serious than WBDF in some cases [3, 4].

Presently, the research on formation damage caused by OBDF has mainly focused on solid phase invasions, wettability changes, and oil traps and there are relatively few studies on why OBDF causes these damages. Cui et al. [4] studied the damage of solid phase invasions to reservoirs, while Korsakova et al. [5] studied the phase distribution and salt exchanges in boreholes during drilling fluid invasion in oil and gas reservoirs. Rong and others [6] used new methods to study the wettability reversal caused by OBDF, Skalli and others [7] studied the wettability effect of surfactants on surface and core in OBDF, and Yan and Sharma [8] studied the wettability change caused by OBDF. Murickan et al. [9] used a relative permeability curve to study trap damages caused by OBDF and WBDF.

To address the lack of damage research for OBDF and why these damages occur, multiple components of OBDF must be further researched, including multiphase fluid states in reservoirs, OBDF properties, and properties of fractured tight sandstone in OBDF environments [10–12].

For the multiphase fluid state of a formation caused by an OBDF intrusion, most studies focus on the oil-water emulsion, but the oil-water emulsion is only in a state of existence [13]. The existing OBDF research is mostly based on the pure oil phase or oil-water two phase type (water-in-oil drilling fluid). In addition to the oil-water two-phase type, oil-oil two-phase, oil-gas two-phase, and oil-gas-water three-phase types are also widespread in the uses of OBDF in China, but these situations are not considered in drilling operations, which directly leads to excessive complex problems in drilling, more serious damage to reservoirs, and even more serious damage to WBDF [14, 15].

The properties of OBDF mainly focus on the aspects of high-temperature stability and suspension stability, which have not been thoroughly solved, thus resulting in a certain difference between reservoir protection technological capabilities and WBDF [16, 17]. The stability problems caused by OBDF emulsification are rarely considered, the changes of wettability and capillary force caused by bubbling in OBDF are only mentioned in a few studies, the chemical changes caused by OBDFs entering reservoirs are rarely considered [18, 19], and the formation of OBDF mud cake and particle size control have been mostly ignored.

The change in properties of fractured tight sandstone in an OBDF environment is one of the key factors causing damage to reservoirs. At present, there are many misunderstandings regarding the use of OBDF. In many cases, OBDF usage does not take into account the actual situation of the formation [20–23]. The use of OBDFs is generally believed to not be complicated when WBDF cannot be drilled smoothly. From the existing research, there is a large misunderstanding of this view. OBDF may not be as suitable as WBDF in some cases. In addition, studies on the characteristics of seepage channels such as fractures and matrix pores in OBDF environments are rare [24–27]. Some common sense errors have been caused by the improper treatment of WBDF environments.

Currently, the research on the formation damage control of OBDFs is mainly based on WBDFs. The theoretical and technical research on formation damage is limited to the scope of water-based fluids. In most cases, WBDF theories and methods rarely take into account the causes of different types or degrees of damage caused by different fluids, although they objectively form a thorough understanding of the reservoir protection effects of OBDF. However, a small amount of OBDF formation damage research has mainly focused on porous formations and few studies have researched fractured reservoirs with ultralow permeability.

The damage causes of OBDF to the fractured tight sandstone reservoir in the Keshen Block of Tarim Oilfield, China, are studied through three aspects: the multiphase fluid characteristics of the seepage channel, the changes in the petrophysical and chemical properties, and the rheological stability of OBDF. OBDF has become widely used in complex formations such as fractured tight sandstone due to the reduced costs of comprehensive uses of OBDFs and mature postprocessing technology. Therefore, based on the study of the formation damage of OBDF, correcting the prejudice of low damage of OBDF over a long period of time is one of the important measures used to effectively improve the efficiency of oil and gas exploitation and to realize the efficient development of oil and gas fields.

2. Experiment Section

2.1. Experimental Materials

2.1.1. Experimental Cores. Taken from the Keshen Block of Tarim Oilfield, China, the size of the core foundation is approximately 25 mm in diameter and 50 mm in length. Core types include matrix cores and fractured cores.

2.1.2. Oil-Based Drilling Fluid. OBDF is mainly made up of drilling fluid additives for field drilling in the Keshen Block. The formula is Diesel + 1.0% organic soil + 1.5% primary emulsifier + 2.1% auxiliary emulsifier + 20% $CaCl_2$ brine (80/20) + 2.5% loss agent + 2.5% lime + 0.5% wetting agent + a weighting agent.

2.2. Experimental Methods

(1) Drilling Fluid Performance Testing. A six-speed rotating viscometer is used to measure the readings at different rotating speeds (600/300/200/100/6/3), and the apparent viscosity, plastic viscosity, and dynamic shear force are calculated according to the standard. API filtration is measured by a medium pressure filtration instrument. The high-temperature and high-pressure filtration instrument is used to measure the high-temperature and high-pressure filtration volume. The demulsification voltage (electric stability) is measured by an electric stabilizer. The experimental reference standard is the National Drilling Fluid Testing Standard "GB/T 29170-2012 Oil and Gas Industry Drilling Fluid Laboratory Testing."

(2) Core Damage Evaluation Experiment. Referring to the standard of the China Petroleum and Natural Gas Industry "SYT 6540-2002 Drilling Fluid Completion Fluid Damage Layer Indoor Evaluation Method," and using the experimental device of core damage evaluation, the device can simultaneously carry out two parallel sample tests to improve the experimental accuracy. This experiment adopts the displacement method: forward direction-reverse direction-forward direction, and the flow of fluid from formation to the wellbore is in the forward direction. The evaluation method for the damage degree is to compare the permeabilities of the formation before and after damage and then calculate the permeability damage rate.

(3) Evaluating the Relationship between Viscosities at Different Temperatures and Shear Rates. A Grace 3600 grade-free heating viscometer was used for this test. The shear rates (S^{-1}) are 1021.38, 510.69, 340.46, 170.23, 10.214, 5.107, 1.702, and 0.851.

Table 1: Basic performance of OBDF (1.86 g/cm^3).

Experimental condition	Apparent viscosity (mPa·s)	Plastic viscosity (mPa·s)	Yield point (Pa)	Filter loss$_{API}$ (mL)	Filter loss$_{HTHP\text{-}API}$ (mL)	Emulsion stability (V)
Before aging	93.0	86.0	7.0	0.6	1.6	984
After aging	67.5	60.0	7.5	0	1.6	959

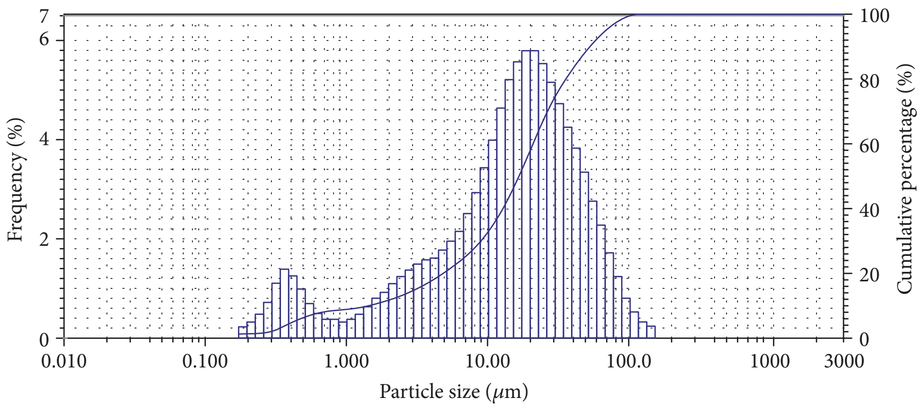


Figure 1: Solid particle distribution of oil-based drilling fluid.

(4) Scanning Electron Microscopy. A Quanta 450 environmental scanning electron microscopy was used for testing.

(5) Clay Mineral Composition Analysis. An X'Pert MPD PRO X-ray diffractometer was used.

3. OBDF and Potential Damage Formation

3.1. OBDF. In drilling engineering, the excellent inhibition performance of OBDF is an important reason for its large-scale use. OBDF takes oil in a continuous phase, which can effectively avoid conventional sensitivity damage, especially water sensitivity damage; low filtration and a relatively strong plugging mechanism greatly improve the reservoir protection; at the same time, OBDF can also effectively reduce scaling and corrosion damage, and the oil phase can effectively reduce friction resistance and reduce engineering accidents.

In most cases, OBDF consists of base oil, organic soil, an emulsifier, a filtrate reducer, a wetting agent, a weighting agent, calcium oxide, and some oleophilic colloids and inorganic ions. In addition to some common additives such as filtrate reducers and weighting materials, the differences in the continuous phase media directly determine the huge differences in their properties compared with WBDF. At the same time, the rheological properties of OBDF are different from those of WBDF because of the noncommon additives such as emulsifiers and wetting agents. Therefore, in most cases, the use and treatment of OBDFs are quite different from WBDFs.

For fractured tight sandstone gas reservoirs in ultradeep wells, OBDF is widely used in the Keshen Block and UDM-2 OBDF uses advanced technology. Taking OBDF with a density of 1.86 g/cm^3, the basic performance of the drilling fluid is shown in Table 1 and the experimental aging conditions are 150°C and 16 h. Solid particle distribution of the oil-based drilling fluid is shown in Figure 1.

Table 2: Pore size distribution in the Keshen Block.

Particle size distribution (μm)	Sample (%) #1	#2	#3	#4
0-0.017	0.00	0.00	0.00	0.00
0.0170-0.0283	5.60	13.39	21.19	67.24
0.0283-0.0471	41.69	61.86	53.29	22.18
0.0471-0.0785	24.34	20.09	21.97	0.00
0.0785-0.1307	19.04	1.43	0.00	6.04
0.1307-0.2176	8.02	3.23	2.86	4.34
0.2176-0.3625	1.32	0.00	0.49	0.00
0.3625-1.6700	0.00	0.00	0.20	0.20

3.2. Potential Damage Formation. Fractured tight sandstone gas reservoirs are characterized by low porosity, low permeability, fracture development, local ultralow water saturation, high capillary pressure, abnormal formation pressure, and high damage potential [28, 29]. The Keshen Block in Tarim Oilfield has all these characteristics and is a typical fractured tight sandstone gas reservoir. The core permeability of the Keshen Block reservoir is mainly distributed between 0.0020 and 0.0680×10^{-3} μm^2. The average core permeability is only 0.0234×10^{-3} μm^2, which denotes an ultralow permeability reservoir. The porosity of the reservoir core is mainly distributed between 3.09% and 10.89%, and the average core porosity is only 5.77%, which denotes a low porosity reservoir. The reservoir physical property analysis shows that the reservoir core porosity in the Dabei block is low, and the average porosity is 5.77%. The reservoir pores are fine (Table 2). Reservoir particles show mainly surface-surface

Table 3: XRD analysis of clay mineral content in the Keshen Block.

Core number	Absolute content of clay minerals (%)	Relative content of clay minerals (%)				Interlayer ratio (%S)
		Illite	Illite/montmorillonite	Kaolinite	Chlorite	
ks2-2-8-61	4.9	52.6	8.3	0.0	39.1	15.0
ks2-2-8-67	2.3	53.4	6.6	0.0	40.0	15.0
ks2-2-8-72	6.2	66.0	8.7	0.0	25.3	15.0
ks2-2-8-84	3.0	58.2	3.1	0.0	38.7	10.0
ks2-2-14-131	3.3	57.0	14.3	0.0	28.7	15.0
ks8-114	6.0	66.4	11.7	0.0	21.8	15.0
ks207-90	6.0	53.3	14.4	0.0	32.3	15.0
ks208-104	8.5	53.9	18.3	0.0	27.9	15.0

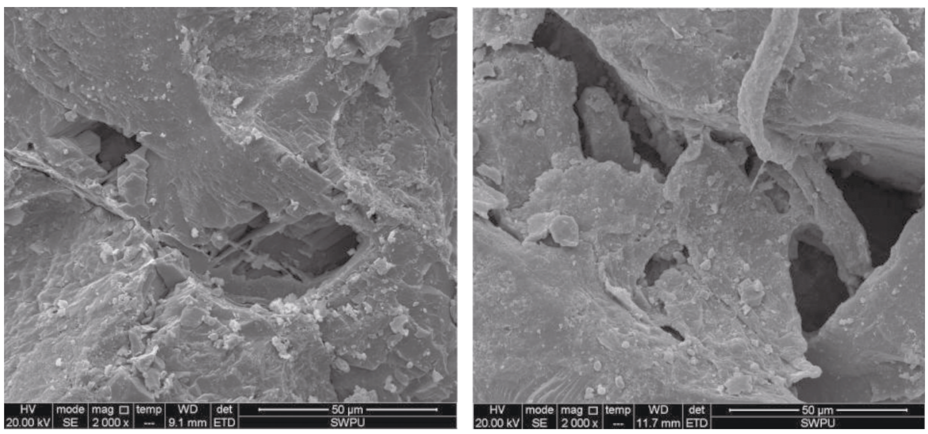


Figure 2: Rock surface morphology without damage.

contacts or line-surface contacts. The contacts between the particles are close, and the porosity is concentrated from 0.80% to 2.70%, with a part less than 0.10%. The rock pores are not uniform. Most areas have no pores and are locally concentrated. The average clay mineral content in the reservoir cores is 5.03%, the illite content is more than 50% (Table 3), and potential formation damage exists. Scanning electron microscopy (SEM) data show that the pore throat of the reservoir is not clear at low multiples (Figure 2), which reflects the characteristics of poor pore development and a poor connectivity of the reservoir in the study area.

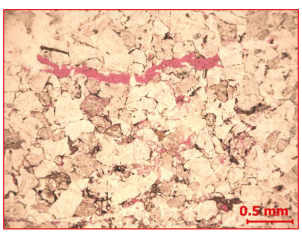
The fissure linear density of 3 wells in the Keshen 1-Keshen 2 gas reservoir was calculated. The Keshen 201 well has the most developed fractures. There are 584 interpreted fractures in the 306 m Paleogene and Cretaceous formations, and the fracture density is 1.91 per m. The Keshen 2 well has 116 interpreted fractures in 141.5 m formations, and the fracture density is 0.82 per meter. The least developed fractures are in the Keshen 202 well with 95 interpreted fractures in a 300 m formation and 0.32 fracture densities per meter. According to the reservoir fracture analysis in the Keshen Block, the main seepage channel type of the reservoir in the block is fractures, followed by larger pores. Reservoir fractures are thoroughly developed, with fracture widths of less than 1-2 mm or even 0.5 mm in some cases, most of which are distributed below 0.1 mm (Figures 3 and 4). By analyzing the cores taken from the target formation, obvious fractures can be found in some cores. The reservoir is characterized by low porosity, ultralow permeability, and compact sandstone. At the same time, the reservoir can generate industrial oil and gas flow. The fractures and microfractures are the main seepage channels of the reservoir.

The pressure coefficients of the target formation in the study block are mostly between 1.75 and 2.20, and the formation's static pressure is high. The formation temperature is mostly distributed between 130°C and 160°C, meaning that it is a high-temperature formation.

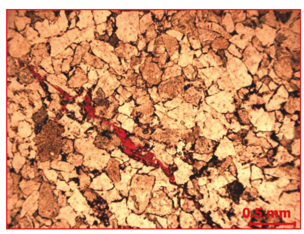
3.3. Potential Damage Factors of OBDF. In most cases, the main potential damage types from WBDF include rock sensitivity damage and a high filtration rate, but OBDF greatly weakens or even eliminates these damages, resulting in a traditional recognition that OBDF can thoroughly protect reservoirs. However, with the combined compositions and mechanisms of OBDF and WBDF, OBDF also experiences serious reservoir damage. Taking UDM-2 OBDF as an example, dynamic damage experiments of the fractured rock cores are conducted and the results (Table 4 and Figure 5) show that OBDF has more serious damage [30]. Therefore, the potential damage factors of OBDFs must be studied.

According to the lithological and physical characteristics of the reservoir, the study object is a low-porosity/ultralow-permeability reservoir. From the pore throat characteristics and fracture characteristics, the pore throat of the reservoir

Figure 3: Schematic diagram of cores of the research block.



(a)



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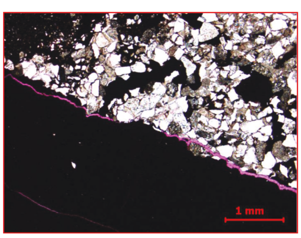

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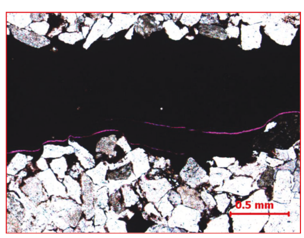

(d)

Figure 4: Thin section analysis of the Keshen Block. (a) Semifilled tectonic fracture (Keshen 207 well: 6998.09 m). (b) Semifilled tectonic fracture (Keshen 207 well: 6998.56 m). (c) Microfracture (0.01-0.05 mm) (Keshen 202 well: 6797.55 m). (d) Microfracture (0.01 mm) (Keshen 202 well: 6797.82 m).

matrix is small, fractures and microfractures are developed, and the pore throat with a relatively high permeability and fractures/microfractures is the main reservoir seepage channel, which is the research focus of damage control technology. The high formation pressure coefficient objectively requires a high suspension stability of the drilling fluid, especially for OBDF; when the high density suspension stability is relatively poor, any safe usage of OBDF is difficult. The formation temperature is high, which requires a high-temperature stability for the drilling fluid; the requirements of high-temperature stability and suspension of the drilling fluid are thus objectively improved, but recreating these conditions for OBDF is difficult. Formation water has a high salinity, so the use of low-salinity drilling fluids must be controlled.

Based on the analysis of the properties of OBDF and the characteristics of fractured tight sandstone gas reservoirs, OBDF is mainly affected by three aspects: its own natural conditions, the interaction between OBDF and rocks, and the nature of OBDF at the contact surface [31]. The most obvious change in the properties of OBDF is its rheological change; rock actions are mainly divided into physical and chemical actions and the coupling effect; the properties of OBDF at the contact surface are mainly a series of fluid characteristic changes after the OBDF contact with rocks and formation fluids.

Based on the analysis of the properties of OBDF and the characteristics of fractured tight sandstone gas reservoirs, OBDF is mainly affected by three aspects: the nature of OBDF themselves, the interaction between OBDF and rocks, and the nature of OBDF at the contact surface [31]. The most obvious change in the properties of OBDF is the rheological change of OBDF; rock actions are mainly divided into physical and chemical actions and the coupling effect; the properties of OBDF at the contact surface are mainly a series of fluid characteristic changes after OBDF contact with rocks and formation fluids.

4. Multiphase Fluid Characteristics of Seepage Channels

The multiphase fluid characteristics in OBDF are mainly embodied in the flow characteristics of different types of fluids with a mixed flow [32]. The fluid includes the OBDF and fluid in the formation. OBDF mainly consists of oil and brine, and the formation fluid mainly includes formation water, crude oil, and gas.

Before OBDF intrudes into the reservoir, oil, gas, and water in the pore throat and microfractures are in a relative equilibrium state and there is generally no interference effect between them. However, when OBDF intrudes into the reservoir, the oil and water phases mix with the fluid in the formation to form a multiphase distribution state of oil, gas, and water (Figure 6). Seepage characteristics will change dramatically with the multiphase flow. Different mixing states may reach different forms that will be directly or indirectly adsorbed or attached to the inside of the seepage channel or

Table 4: Experimental results of dynamic damage (kerosene displacement).

Core	Number	Permeability before damage (10^{-3} μm^2)	Permeability after damage (10^{-3} μm^2)	Fluid loss (mL)	Permeability recovery rate (%)
Natural fractured core	3	2.3988	0.6875	0.4	28.66
	4	3.0395	0.9854	0.4	32.42
Artificial fractured core	6	8.4752	4.5238	0.9	53.38
	7	10.4584	3.6846	0.7	35.23

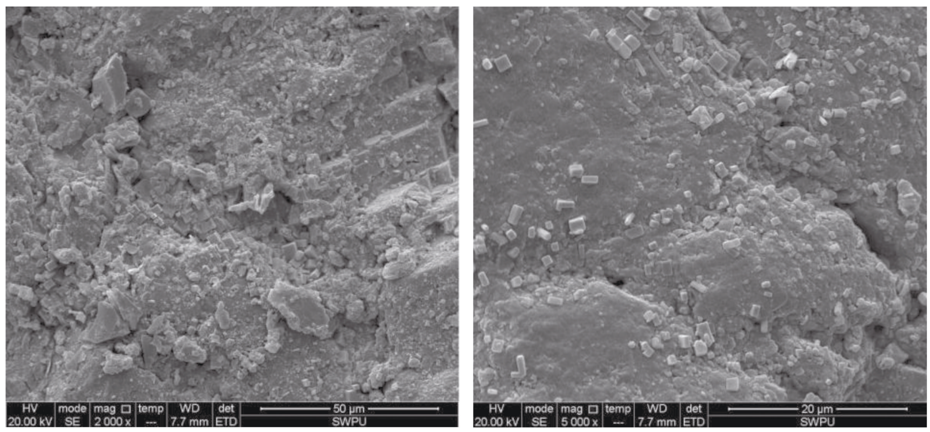

Figure 5: Rock surface morphology after the dynamic damage test.

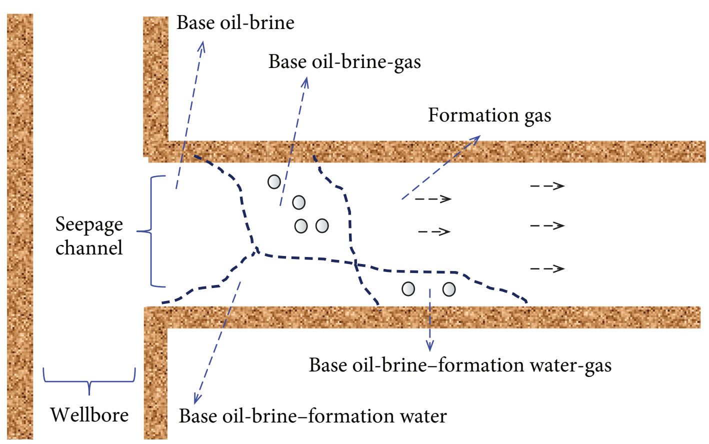

Figure 6: Distribution of oil-gas-water after OBDF invasion (the dotted lines are fracture walls from different zones, and the text indicates the liquid mixing state in different zones; this zoning is an idealized figure for more clearly described multiphase fluids, and the actual fluids are more complex).

they may form a multiphase seepage zone; all of these forms will cause reservoir damage.

The existing space corresponding to the existence of the multiphase fluid is also related to the magnitude of the effect of the multiphase fluid. Most existing studies have found that the main seepage channel of the fractured gas reservoir itself is a fracture itself, while the matrix pore throat showed a relatively small role in the storage and seepage. However, according to the research and engineering practices of the Sichuan Basin in China, the matrix porosity also plays an important role. For fractured tight sandstone gas reservoirs, the existing research and corresponding reservoir protection measures are mainly aimed at fractures. In most cases, the influence of the matrix pore damage is ignored. Taking the fractured tight sandstone gas reservoir of the Keshen Block in China Tarim Oilfield as an example, the fracture is the main seepage channel that can be observed and the matrix pore permeability is less than 0.03×10^{-3} μm^2, although the partial permeability is approximately 1.0×10^{-3} μm^2. Many studies have shown that a larger pore throat and some ultra-fine pore throats connect fractures to ensure continuity in the seepage channel. Therefore, the characteristics of multiphase fluids in pores and fractures must be evaluated.

Most of the existing studies posit that the main seepage channel of fractured gas reservoirs is a fracture, and matrix pores play a relatively small role in storage and seepage.

Table 5: Rheological test of oil base drilling fluid in its original state.

Shear rate (S^{-1})	Viscosity (mPa·s) 40°C	50°C	60°C	70°C	80°C	90°C
1021.38	38.87	36.72	32.51	28.88	25.75	23.20
510.69	47.97	45.43	39.16	33.88	30.55	27.41
340.46	60.80	57.57	50.23	43.18	37.89	31.13
170.23	82.24	77.54	67.56	57.57	51.70	41.71
10.214	597.23	538.49	509.12	421.00	381.84	323.09
5.107	1507.76	1076.97	979.07	861.58	783.25	685.35
1.702	3289.66	2995.94	2643.48	2408.50	2173.53	1879.81
0.851	6344.35	5991.88	5051.98	4464.54	4112.08	3642.12

However, according to research and engineering practices in Sichuan Basin, China, matrix pores also play an important role. For fractured tight sandstone gas reservoirs, existing research and corresponding reservoir protection measures mainly focus on fractures and in most cases neglect the impact of matrix pore damage. Taking the fractured tight sandstone gas reservoir in the Keshen Block of Tarim Oilfield as an example, the fracture is the main observable seepage channel. The matrix pore permeability is less than 0.03×10^{-3} μm^2, but there are large pore throats with partial permeability of approximately 1.0×10^{-3} μm^2. Research shows that larger pore throats and some ultrafine pore throats play a role in communicating fractures and ensuring the continuity of seepage channels. Therefore, the characteristics of multiphase fluids in pores and fractures must be evaluated.

According to the possible forms of fluid occurring after OBDF intrusion, different mixing states are classified and the possible physical and chemical changes for each form are studied. On this basis, the change trend of the seepage channel size caused by different mixing states is predicted and the possible damage caused by the fluid is judged. OBDF has several characteristics including that the oil phase is a continuous phase, the water phase is a dispersed phase that is relatively small, and the fluid distribution is divided into the following types: base oil-brine, base oil-formation water, base oil-formation gas, base oil-brine-formation gas, base oil-crude oil, base oil-brine-formation water, base oil-brine-formation oil, base oil-brine-formation oil-formation gas, and base oil-brine-formation water-formation oil-formation gas. For other forms of distribution, due to the relatively small amounts of brine and crude oil, they may be referred to in the above listing without further consideration.

4.1. Base Oil-Brine. The distribution state of the base oil-brine form is the flow of the OBDF itself in the fractures and is the most common flow state in the seepage channel. When the OBDF flow is in the original state, the flow in the fractured sandstone reservoir may divide into a fractured flow and porous flow; these two flow types are influenced by the OBDF properties, and Table 5 shows the rheological test results of OBDF in the original state that was used in the oilfield.

The fracture flow is mainly the flow of OBDF within the fractures. The flow pattern shows the characteristics of plastic/pseudoplastic fluids. The main reason for this plastic/pseudoplastic flow pattern is the interactions between the oil phase, organic soil phase, granular material, and other additives. Organic soil is a modified bentonite. When it enters the OBDF, the internal interval of the organic soil enlarges, forming a thinner sheet structure and connecting with each other and forming a spatial network structure and exhibiting plastic fluid characteristics.

Flows in fractures are often subject to large flow pressure differences, which reduces the flocculation state of organic soil and particles in OBDF. With this kind of flow, the OBDF flows faster and the fluid contact space is mainly the wall of the seepage channel. The main reason for reducing the size of the seepage channel is the adsorption and adhesion of the wall based on the wettability of the fluid surface. Without considering the attachment of the oil-loving particles, the adsorption capacity of the base oil-brine two-phase fluid on the fracture surface is very limited, and there is not much of an OBDF effect.

For porous structures, the pore throat of the fractured tight sandstone gas reservoir is small and the capillary force is the main reason [33, 34]. OBDF flow comes from fluid dynamics and capillary force inhalation, showing a gradual decline in flow efficiency, and stops flowing after forming a certain length of a liquid retention zone.

4.2. Base Oil-Brine-Formation Gas. The base oil-brine-formation gas form is the distribution of oil-gas-water formed by gas invasion after OBDF intrudes into the reservoir, and it is also a universal state of a fractured tight sandstone gas reservoir. In essence, this three-phase state presents the flow pattern of the OBDF after being invaded by the gas; there is a difference between the fracture and the pore flow for the reservoir, and there is a certain difference of the mechanism between this pattern and the original OBDF flow. After the gas invasion, OBDF will be filled by bubbles of different sizes. An oil-gas interface and a small amount of gas-water interface state will be formed in the OBDF. The oil-water interface can be weakened to a certain extent. OBDF will change in rheological stability to a certain extent and will also affect suspension efficiency. The weakening of the interface will be strengthened with the increase of gas intrusion, which may eventually aggravate the damage.

In this area, the OBDF flow rate will decrease, forming a certain length of a three-phase mixing zone; the distribution

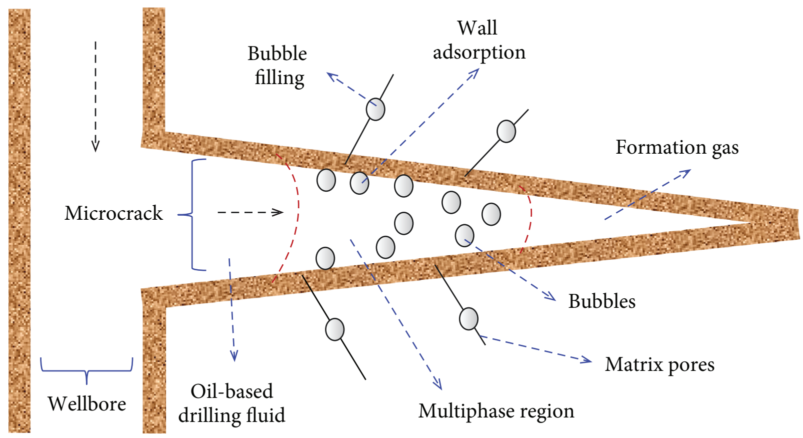

Figure 7: Three-phase seepage of oil-gas-water.

Table 6: Relationship between shear rate and shear stress of OBDF (50°C).

Shear rate (S^{-1})	Shear stress (Pa)					
	80/20	70/30	60/40	50/50	40/60	30/70
1021.38	7.83	14.03	17.94	102.60	151.20	328.50
510.69	4.84	8.79	12.21	70.40	100.80	253.60
340.46	4.09	6.70	9.94	55.40	79.20	191.40
170.23	2.76	4.72	7.45	40.50	58.40	153.30
10.214	1.15	2.11	3.51	21.30	29.30	74.70
5.107	1.15	2.09	3.38	20.50	28.00	69.50
1.702	1.06	1.75	2.80	16.60	22.10	57.60
0.851	0.96	1.61	2.30	12.20	16.40	39.80

of bubbles will increase along with the wellbore in the formation direction, and the three-phase fluid will adsorb on the fracture wall to varying degrees, but this adsorption is not stable. With the continuous invasion of OBDF, the gas phase will be reduced, as shown in Figure 7. For the porous region, the three-phase flow enters the pore via the hydrodynamic force and capillary force. Because of its high deformability and different size distributions, bubbles fill and plug the pore, which to some extent reduces the invasion of the other two phases and indirectly reduces the damage caused by the oil-water phases [35]. The filling effect of the bubbles in the pore also exists in the microfractures.

4.3. Base Oil-Brine-Formation Water. Generally, for fractured tight sandstone gas reservoirs, the water saturation of the formation is relatively small, but during the OBDF invasion, this formation water enters into the OBDF, which will have a greater impact on the performance of OBDF in the microregion. Generally, brine and formation water differ greatly in basic properties such as salinity and pH and cannot be directly mixed into one phase. Base oil-brine-formation water exists in a pseudothree-phase state. Taking OBDF as an example, a formation water intrusion was simulated and its rheological properties and flow patterns were evaluated for different oil-water ratios at 50°C (Table 6).

The evaluation shows that the change in the oil-water ratio will greatly change the flow state of OBDF. When formation water enters the OBDF, it will break the oil-water two-phase equilibrium of OBDF, change the nature of the oil-water interface, and even destabilize the emulsion when the water intrusion becomes too large.

In the area where the OBDF contacts the formation, a transition zone will be formed. Fractures and porous reservoirs in this area will be greatly affected, and serious damage may occur. For fractured reservoirs, when the formation water content is low, the damage mainly comes from wall adsorption; when the formation water content is large, the oil-water interface of OBDF is destroyed, the wettability of the wall shows diversity, and the mixed adhesion of the water phase and oil phase on the fracture wall is the main state, which will also cause regional damage.

For the pore structure, the water phase is the main filling phase in the pore, and the OBDF will continue to displace after invasion. From the microscopic phenomena of OBDF flowing in the pore, this displacement is not serious but is more likely to change the wall's wettability. With the capillary force, the original hydrophilic wetting wall does not necessarily show a wettability change, so the capillary force acting on OBDF in the pore should be considered instead.

4.4. Base Oil-Brine-Formation Water-Formation Gas. For fractured tight sandstone gas reservoirs, this oil-gas-water distribution state of the base oil-brine-formation water-gas form should be common. The multiphase existing area

Table 7: Stress sensitivity of fractured tight sandstone gas reservoir in the study area.

Core	Core number	Permeability ($10^{-3}\ \mu m^2$) 2.5 MPa	20 MPa	2.5 MPa	Damage rate of permeability (%)
Matrix core	111	0.0249	0.0096	0.0115	25.84
	129	0.0106	0.0036	0.0083	21.80
Fracture core	115	27.4762	1.4855	3.6195	86.83
	119	12.3547	0.5964	1.1564	90.64

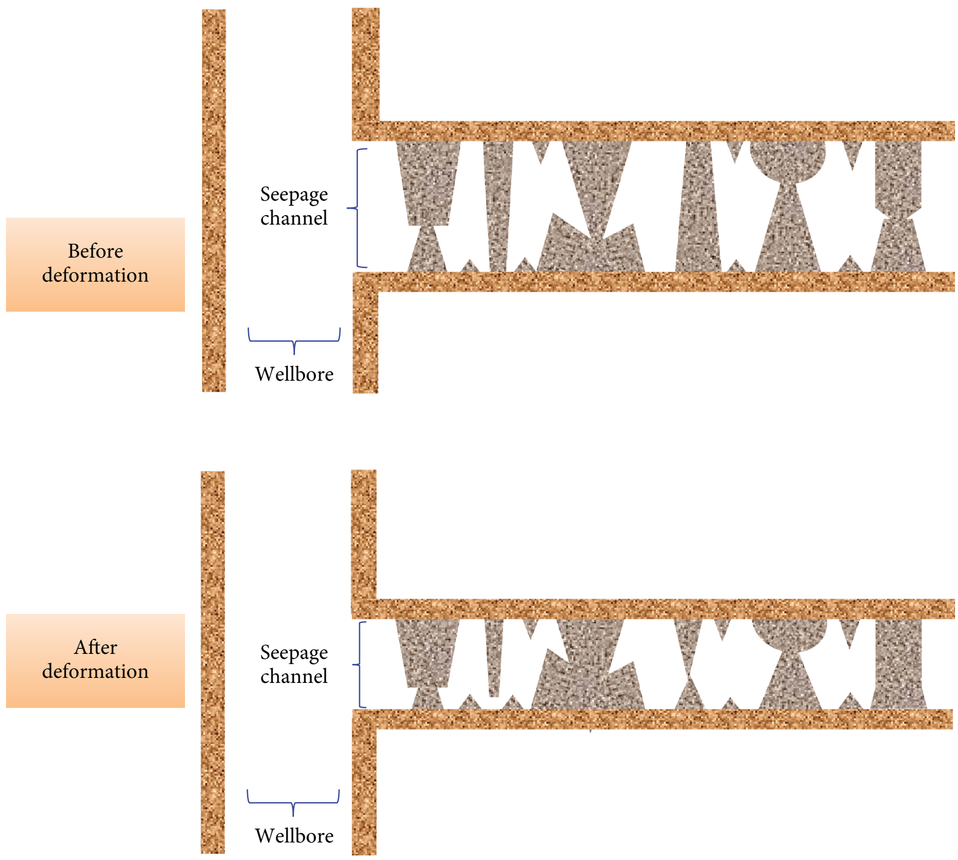

Figure 8: Comparison of the changes of asperities before and after stress.

formed by OBDF entering the reservoir is unclear, as shown in Figure 5. The oil-water distribution state of the base oil-brine-formation water-gas form is also the most common multiphase existing state. In this state, from the fluid level, the change characteristics of the fracture wall and pore structure use the mixture of the first three states and there are many situations in which this may occur.

For the base oil-brine-formation water-gas distribution area, the formation water and oil-based drilling will fill some bubbles in the contact area between the OBDF and formation water. When the formation water saturation is high, the OBDF will move forward after contacting with the formation water. Based on the hydrophilic and wetting properties of the surfaces of most minerals, the mixed fluid will aggravate the attachment on the fracture wall and this kind of attachment is more likely to release bubbles after the OBDF intrudes in large quantities, which are not easy to wash away.

For the porous structure, the capillary force still plays a dominant role. Increased water content will increase the absorption power of the water-wet rock, resulting in a more serious capillary force. For formations with a low water saturation, the mechanism is similar to the high saturation mechanism. Bubbles also play a role in blocking microfractures and pores.

4.5. Base Oil-Brine-Formation Oil and Other Derived States. Base oil-brine-formation oil and other derivative states are not listed in Figure 6. This is because for fractured tight sandstone gas reservoirs, the formation's oil content is miniscule, while the OBDF itself takes the oil phase as a continuous phase, and thus the small amount of formation oil with different properties will not change greatly after invasion. Formation oil itself contains more asphaltene, gum, and lipophilic particles, but when it enters OBDF, it fuses with the

Table 8: Evaluation of water-phase alkali sensitivity.

Core number	Permeability at different pH values (10^{-3} μm^2) 7.0	9.0	11.0	13.0	Permeability recovery rate (%)	Damage degree
125	44.03	30.31	13.87	8.92	20.25	Serious
133	65.30	51.31	31.29	6.85	10.49	Serious

asphaltene, gum, and lipophilic particles existing in OBDF to form a new OBDF. This kind of OBDF has very little difference from the original fluid with regard to the surface properties for fractures and pore throats.

5. Effect of Rock Physics and Chemical Changes

The change in rock strength here mainly refers to the change of mechanical characteristics of rocks on the wall of the seepage passage after OBDF intrusion, and it is also the mechanical expression of the coupling effect of fluids, rock physics, and chemistry.

5.1. Physical Effect. In the drilling operations of deep and ultradeep wells, the overbalanced drilling method is often used. The fluid column pressure applied to the formation by drilling fluid is greater than the formation pressure. This pressure difference is the main cause of drilling fluid intrusion into the reservoir, and it also affects the mechanical properties of surrounding rock to a certain extent.

For the fractured tight sandstone gas reservoirs, the matrix rock itself is more compact and the degree of mechanical impact will be relatively small; however, because of the objective existence of fractures, the pressure applied by OBDF will act on the fractures and the pressure fluctuations acted on the fractures in the formation will have a greater change. Taking the fractured tight sandstone gas reservoir in the Keshen Block as an example, the stress sensitivity with the variable pressure in the standard experimental procedure (standards of the petroleum and natural gas industry of China: SY/T 5358-2010 formation damage evaluation by the flow test) was evaluated (Table 7). The sensitivity of the fracture to the external pressure is stronger than the matrix sensitivity where the dry core is not doped with other factors.

The main reason for such a great change in the gas seepage ability in fractures is that the wall properties of fractures are greatly changed. For the seepage channel, the fractures on the wall are rough and inhomogeneous, showing different sizes of asperities, and the distribution of the asperities vary widely in the two fracture walls. When subjected to external force, the asperities that originally support each other appear to have an elastic deformation by squeezing. When the stress exceeds a certain degree, the asperities will cause plastic deformation, which is the main reason that the permeability decreased rapidly at the initial state and changed slowly during late period; the change in asperities is irreversible to a large extent.

When OBDF exists, the particulate material deposits on the wall of the fractures, which does not react chemically with the rock. The particulate matter in the OBDF mainly includes weighting agents, cuttings, organic soils and some reservoir

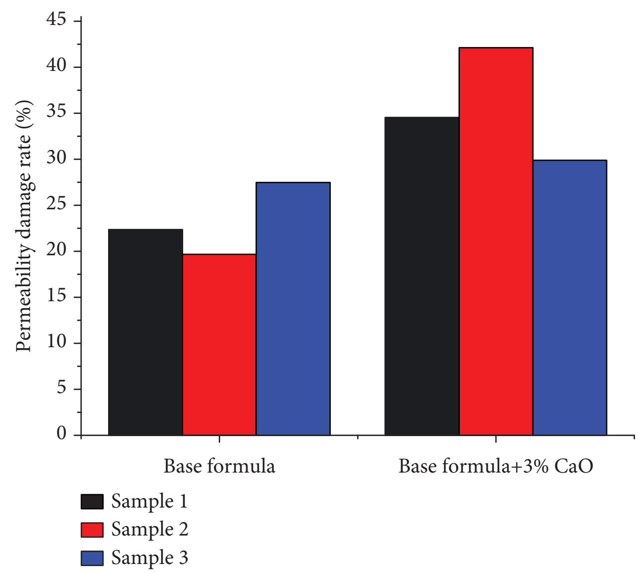

Figure 9: Evaluation of alkaline sensitivity of OBDF.

protection materials. This particulate matter adsorbs and adheres between the asperity bodies to form a layer of granule cover. This has a large impact on the mechanical properties of the rock when subjected to external forces. When the asperity is deformed by force, it is prone to collapse and form a new asperity structure (Figure 8).

In some cases, after the OBDF invasion, in addition to the force that is directly applied to the borehole by OBDF, the physical effects also include the filling effect of solid particles in the zone between asperities that indirectly affect the fracture strength. However, parts of solid particles still attach onto the asperities of the fracture surface when the pressure difference drops; the seepage channels become small, which will cause a large change in the permeability. In this case, explaining the effect of physical action on the seepage capacity is inappropriate. Therefore, there is a need for a comprehensive evaluation of the capacity's mechanical effects with fluid participation.

After the invasion of OBDF, the capillary force in the microfractures and capillaries will cause the oil phase to enter, and this existence is not easily removed. For fractured tight sandstone gas reservoirs, the initial water saturation is lower than the irreducible water saturation in most conditions. When the OBDF intrudes, it will cause greater oil trap damage, which is affected by the changes of the invasion amount, formation pressure and saturation.

5.2. Chemical Effect. The chemical action of the rock strength change mainly comes from the action of OBDF on the well perimeter and the wall of the seepage passage. Unlike WBDFs, the chemical action of OBDF on rocks mainly concentrates on alkalinity, and the wettability of rock surface may also have a weak impact [36]. When the oil-water ratio is small, a large amount of the water phase can also cause other forms of damage.

The chemical effect of rock strength change is mainly due to the effect of OBDF on the wellbore and the wall of the seepage channel. Different from water based drilling

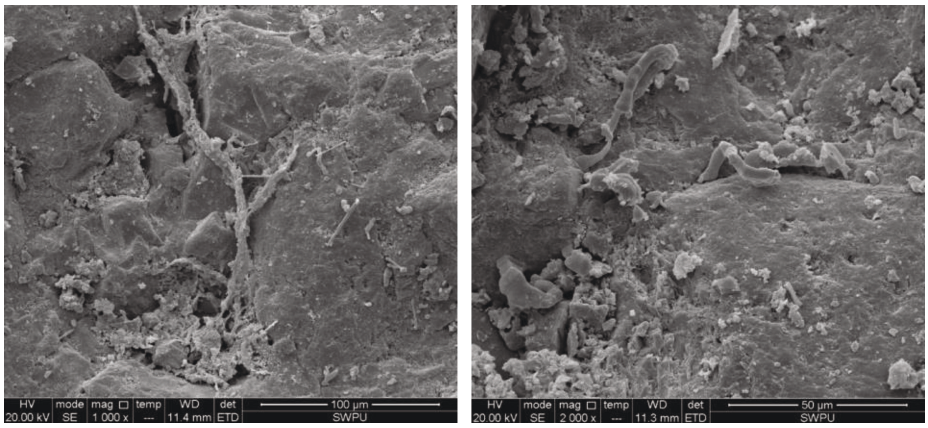

Figure 10: Adsorption of macromolecule treating agents after soaking in OBDF.

fluids, the chemical effects of OBDF on rock are mainly concentrated in alkaline action, and wettability of rock surface may also has a weak impact [36]. At the low oil-water ratio, a large number of water phase will also cause other forms of damage.

The alkaline effect of the OBDF mainly presents as the liquid with a high pH value having an alkali effect on the rock, causing structural changes to the alkali-sensitive minerals in the rock. With the erosion of OBDF, the alkaline minerals fall off, migrate, precipitate or form new colloidal substances that affect the seepage capacity of the seepage channel. Taking the Keshen Block as an example, a water-phase alkali sensitivity evaluation was carried out and the experimental method is based on the standard of oil and gas industry of China "SY/T 5358-2010: formation damage evaluation by flow test," and the results is shown in Table 8.

Since the pH value in the OBDF is mainly the pH value of the water phase, the alkaline treatment agent mainly faces the dispersed water phase in OBDF, while maintaining the stability of the water phase requires the action of emulsifiers. Based on this situation, the basic effects of OBDF can only be evaluated based on the following formula: base oil + 1.5% primary emulsifier + 2.1% auxiliary emulsifier + 20% $CaCl_2$ brine. This is also the reason for the separated water-base sensitivity evaluation. A 3% CaO alkaline treatment agent was added to the base formula to evaluate the damage to the cores by the base formula before and after adding the calcium oxide. The result is shown in Figure 9.

The experimental results show that with the changing formation water pH, the alkali sensitivity damage is serious in the Kenshen Block. The experiment shows that the alkaline single effect severely damages the reservoir and the damage exists objectively in both the water base drilling fluid and the oil base drilling fluid. The alkaline treatment agent in OBDF caused a certain extent of damage, but the damage degree was not serious when compared with the alkaline single effect. The main reason for the decrease in the alkali-sensitive effect of OBDF is that the emulsion itself is attached to the surface of the rock. At the same time, the water phase of the OBDF itself is the dispersed phase and the content is low, which indirectly causes the alkali sensitivity damage degree to be low.

A previous study has shown that the elastic deformation of rock soaked in alkaline liquid is decreased and plastic deformation occurs earlier after soaking in alkaline liquid [37]. This is due to the high pH fluid immersion; the asperities of the fracture wall surface and other structures will be destroyed, and the pore structures of wall interior are damaged. These results show that the rock support capacity decreased, and large changes appeared in the seepage ability.

However, as mentioned previously, particles will deposit, accumulate, and adsorb between the asperity spaces on the wall of the fractures and indirectly affect the mechanical properties of the rock. The processes of accumulation and adhesion are physical changes, but when the wettability of the rock wall changes, the particles that have the same wettability as the wall will accumulate and adsorb more easily on the wall. OBDF contains a wetting agent that can change the wettability of the seepage channel wall from hydrophilic to lipophilic. Then, the rock can adsorb the accumulation of the lipophilic substance in the OBDF on the surface, which influences the strength change of the rock to a certain extent. The adsorption of the treatment agent on the rock also includes the polymer or macromolecule treatment agents in the OBDF [37] (Figure 10), which adsorbs and retains at the pore or fracture wall and blocks the seepage channel with its macromolecular size, resulting in reservoir damage.

When the oil-water ratio is relatively low, the water molecules combine to form larger water particles and the oil-water interface weakens. When the water phase is adsorbed on the wall of the seepage channel and if the change of the wettability of the wall is not stable, the water will come into contact with the rock directly and enter into the reservoir to form water phase damage. Taking the tight sandstone gas reservoir in the Keshen Block as an example, rocks will generate strong water sensitivity, salt sensitivity, and alkali sensitivity damage, which will change the rock properties to a certain extent; the damage was affected by the water content of OBDF.

The change in rock strength is caused by the change in the effective stress of the rock. This change is composed of two parts: body deformation and structural deformation. The body deformation of the rock is caused by the deformation of rock skeleton particles, and the structural deformation is caused by the change of the arrangement mode of skeleton particles. For the fractured tight sandstone gas reservoir example, the reservoir change is mainly a body deformation, which is reversible, and the stress sensitivity of the matrix can explain certain problems (Table 4). For fractures under stress, the asperities produce body deformation, the destroyed fracture surface will produce a new asperity structure, the arrangement mode of asperity particles changes, the rock pore and skeleton volumes are changed, and the stress sensitivity is increased.

For fractured tight sandstone gas reservoirs, the changes in rock strength reflect the change characteristics of fractures, while our previous study focused more on the effect of strength changes on fractures in a closed state. In drilling engineering, the expansion of fractures is the most important factor affecting the flow of OBDF in fractured reservoirs. The main cause of fracture propagation comes from the drilling pressure difference between the wellbore and the formation through OBDF. The fracture tip in the formation is easy to form splitting with differential pressure, which is close to the principle of hydraulic splitting. However, the splitting effect of OBDF is affected by different factors, including the characteristics of the rock itself, the interfacial tension properties of OBDF, the geometric characteristics of fractures, and the drilling pressure. Concurrently, the pressure fluctuation caused during the drilling process will also affect the expansion of the fractures. Taking the tight sandstone gas reservoir in the Keshen Block as an example, in our previous study, the density and opening degree of fractures in several wells of the block are analyzed and summarized. The distribution of the fracture width of the reservoir is wide, and the fracture width changes with the drilling fluid invasion. The large fracture width also causes the loss of drilling fluid and other damages.

6. Rheological Stability of OBDF

Rheology is the basic performance of the drilling fluid, which reflects its flow and deformation properties. The commonly used parameters include apparent viscosity, plastic viscosity, shear force, and so on. OBDF is more susceptible to effects from external factors than WBDF, including temperature, pressure, oil content, particle size, particle concentration, and oil-water interface energy. For practical engineering, rheological properties, suspension problems, and the high-temperature stability of OBDF are the main technical bottlenecks that limit the application of OBDF. To solve these problems including suspension, the rheological performance must be adjusted. If the OBDF is relatively stable at a certain range, many OBDF problems can be solved.

According to the deformation properties, most of the oil-based drilling fluid is plastic or pseudoplastic fluid and the rheological model can also be referred to as a Bingham model or power law model. The OBDF flow is more inclined to be a pseudoplastic fluid in theory, which should be verified in future experiments.

OBDF has obvious rheological instability, while the WBDF instability is relatively small, which is mainly due to the difference between the oil and water properties. Generally, even at a very small temperature range, the viscosity of the oil phase decreases rapidly with the increase of temperature, while the formation temperature is more than 100°C. In the continuous phase, the oil phase is a carrier for a series of treatment agents such as weighting materials and organic soils. The high temperature and high pressure quickly weaken the rheological properties (Figure 11), resulting in an insufficient OBDF amount for suspending excessive particulate matter. After entering the reservoir, the OBDF will settle quickly and cause a series of damages.

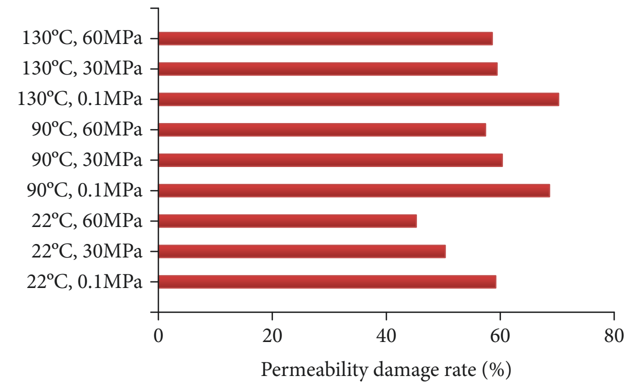

Figure 11: Evaluation of damage experiment at high-temperature and high-pressure conditions.

Controlling the water phase activity is beneficial to borehole stability. Therefore, the commonly used OBDF is usually in a water-in-oil emulsion and the oil phase and the oil-water interface contents are formed by corresponding treatment agents that can easily influence the stability of OBDF. When the amount of water is large or the water intrusion amount is large, the oil-water interface will decrease, which leads to instability in the OBDF and even in the oil-water separation. In this case, when the OBDF enters the reservoir, the actions of the solid phase and the liquid phase will cause serious damage to the reservoir.

In summary, the stability of rheological properties determines the stability of the OBDF and determines whether the OBDF can play a role in the rapid sealing of a reservoir with particles. The study of the rheological properties of OBDF requires further research through OBDF applications.

7. Research Direction of OBDF Damage Control

7.1. The Key Problem of Damage Control. From the point of view of the formation mechanism of OBDF damage, OBDF causes damage to fractured tight sandstone gas reservoirs due to its rheological properties, changes in rock properties, and multiphase flow characteristics. However, based on the formation mechanism, the damage control process must provide an accurate description of the damage characteristics of OBDF to the fractured tight sandstone gas reservoir and how to achieve an accurate plugging of the reservoir [10, 38–40].

Based on this study's research, the potential damage factors involved are classified into four main types: fluid compatibility type, particle combination type, wall morphology change type, and reservoir property type. These types also include a variety of subdivided damage factors, which are specifically classified as follows:

(1) *Fluid Compatibility*. Fluid compatibility mainly refers to the compatibility between the OBDF and rock or fluid; the OBDF damage caused by compatibility mainly includes (1) OBDF and rock are not compatible: alkaline damage and wettability change, and (2) OBDF and fluid are not compatible: emulsion plugging.

(2) *Particle Combination Damage*. Particles include solid phase and nonsolid phase types. Solid phase particles include weighting materials, cuttings, organic soil, reservoir protection materials, and so on [41]. Nonsolid particles include asphaltene, polymer treatment agents, and other nonsolid particles. The main damages include the following: particle migration, solid particle plugging, and chemical adsorption.

(3) *Formation Properties*. The damage to formation properties is mainly the damage caused by the properties of the fractured tight sandstone gas reservoir, which mainly includes oil phase trapping, pressure and temperature characteristics, wetting changes, oil phase adsorption, stress sensitivity and particle sedimentation, gas or water intrusions, and so on.

7.2. Research Direction of Damage Control. The main purpose of reservoir protection theory and technology is to protect a reservoir from damage or be subjected to less damage from drilling fluids. The methods to achieve this goal are mainly derived from two aspects: reducing invasion and fast plugging. However, from the technical and engineering points of view, both are aimed at reducing invasion as the ultimate goal and rapid plugging is the action needed to reduce invasion. The current OBDF damage control system is faced with technical problems, including several aspects: the downhole properties of OBDF are different, the geological characteristics of fractured gas reservoirs are complex, and few new technologies and new materials that are suitable for the damage control of OBDF exist.

Thus, the main goal should be to reduce the fluid invasion into the reservoir. The fluid invasion includes two sources: from solid particles and from the liquid phase. Although both types cause a great deal of damage, there are obvious differences between the microscopic damage mechanism and the methods of removing damage. From this viewpoint, the type and size distribution of solid particles and fluid types should be the important factors that affect the reservoir protection. Rapid plugging is used to overbalance drilling or microbalanced drilling; new technology and new materials are needed to more effectively execute rapid plugging.

Determining how to achieve damage control for OBDF, simply speaking, mainly includes fracture analysis, OBDF performance regulation and maintenance, optimizations of engineering operations, and introductions of new materials and ideas. In combining the formation mechanism and potential damage factors of OBDF, based on the characteristics of fractured tight sandstone gas reservoirs, the technology selection, material selection, system construction, and so on should be considered to form a fast and efficient damage control scheme for OBDF.

8. Conclusions

(1) Both OBDF and WBDF have formation damage, but there are many differences between them, which include emulsion plugging, wettability change, oil phase trapping, oil phase sensitivity, and so on. When OBDF enters into a formation, the change of OBDF properties, multiphase characteristics of seepage channels, and the physical and chemical properties of the rocks are the main reasons for the OBDF damage to the fractured tight sandstone gas reservoir

(2) Base oil-brine and base oil-brine-formation gas are the main fluid distributions in seepage channels, while other forms of distribution are of little importance due to the relatively small amounts of brine and crude oil present. However, many other forms emerge in a certain area, the distribution will also cause serious damage. Compared with the water base drilling fluid, the effects of physical and chemical change are relatively low, but the increase in fracture lubricity, emulsification effect, and oil adsorption can also cause reservoir damage that is distinct from damaged caused by water-based drilling fluid. The special rheological properties of OBDF can lead to suspension stability and emulsion stability in high-temperature and high-pressure conditions, resulting in great differences of wellbore fluid properties that bring a series of damages

(3) The key problems for damage control of OBDF are an accurate description of the damage characteristics of OBDF on fractured tight sandstone gas reservoirs and achieving an accurate plugging of the reservoir; the main control idea is to reduce the invasion of OBDF, and new materials and technologies are needed to achieve rapid plugging

Data Availability

The data of the study have been attached to the article and supplementary material; all data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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