INTRODUCTION

With the world’s conventional oil and gas resources exploitation entering the middle and late stages, the number of deep wells and ultra-deep wells for tight oil and gas development has increased dramatically.\(^1,2\) In the process of deep well drilling, oil-based drilling fluid is widely used to solve the problem of unstable borehole lining in deep well formation. However, its use also brings problems of underground and surface environmental pollution, damage to effective seepage channel, which seriously restricts its further application.\(^3\)
The drilling target layer of Tarim Basin in China has exceeded 8000 meters. The general lithology of this type of formation is tight sandstone or carbonate rock. The permeability of rock matrix is mostly less than 0.1 mD. However, fractures/micro-fractures are widely distributed in the strata, which are the main seepage channels of oil and gas reservoirs. When foreign fluid such as oil-based drilling fluid intrudes into fractures/micro-fractures in drilling process, it will interact with fluids and rocks in formation, including particle accumulation and plugging, emulsion adsorption, liquid trapping and other damages. These damages will seriously affect the ability of formation oil and gas to migrate to wellbore. Some research has been carried out on the reservoir damage mechanism and prevention countermeasures of oil-based drilling fluids, but these studies mainly focus on theoretical research or laboratory experiments, and the theoretical or experimental studies are scattered, and they fail to carry out specific and in-depth design according to formation characteristics or the nature of drilling fluid. There have been many studies on the problem of reservoir damage of oil-based drilling fluids. This kind of research has been receiving more and more attention in the near future since the 1990s. The existing research focuses on the analysis of single damage mechanism and mainly focuses on liquid traps, wettability, and other research hotspots. A few systematic studies rarely consider the comprehensive effects of multiple factors. On the other hand, the existing research generally selects specific materials directly to carry out experiments, lacking pertinence, indoor evaluation is difficult to fully consider the formation factors. At present, the primary task of deep/ultra-deep well drilling is to ensure the smooth completion of the operation. Reservoir protection has been widely proposed, but it has not received much attention. Therefore, the research has seldom been directly applied to the field, resulting in little systematic research. This also causes engineers to neglect the reservoir protection of oil-based drilling fluid from the aspects of drilling cost and engineering schedule.

In our previous research, through the analysis of reservoir characteristics in Keshen block of Tarim Basin, China, the experimental analysis and interpretation of the damage mechanism of the oil-based drilling fluid at both the macro- and micro-angles were proposed. Reservoir protection measures and several wells have been applied on site. Field tests show that the optimization design of reservoir protection of drilling fluid has a good effect. However, my research does not analyze and summarize the influencing factors and design ideas of reservoir protection from a very detailed perspective, and there are still certain defects in theory.

In view of the current lack of systematic research on the protection of oil-based drilling fluid reservoir, the paper systematically summarizes a series of achievements made by the research group in the early stage and carries out research on the protection methods of oil-based drilling fluid reservoir in deep fracture tight gas reservoir. The research work summarizes the particularity of oil-based drilling fluid reservoir protection, defines the main influencing factors of oil-based drilling fluid reservoir protection, and then forms a set of reservoir protection method suitable for deep fracture tight gas reservoir from many aspects such as reservoir protection design idea, system construction, and simulation evaluation, which provides a direction for the reservoir protection of subsequent oil-based drilling fluid.

2 | EXPERIMENTAL PREPARATION AND METHODS

2.1 | Experimental materials and instruments

Experimental drilling fluids: oil-based drilling fluids prepared indoors according to field formulation and additives. The oil-based drilling fluids produced by two companies are mainly used in Keshen block of Tarim Oilfield, namely Anton oilfield services group and SPT Energy Group Inc, with densities of 1.60, 1.75, 1.90, and 2.05 g/cm³, respectively.

Formulation of oil-based drilling fluid in simulation experiments: base oil + 1.0% organic soil + 1.5% main emulsion + 2.1% auxiliary emulsion + 20% CaCl₂ brine (80/20) + 2.5% filtrate reducer + 2.5% lime + 0.5% wetting agent + weighting material, density is 1.86 g/cm³, which is one of the representative densities in Keshen block.

Experimental fluid: ordinary kerosene, formation water.

Experimental cores: steel cores; artificial fracture cores in Keshen block, cores sampled at the same time in the same well at the same layer.

Experimental instrument: DTSH-III High-temperature and high-pressure dynamic evaluation device (Figure 1). Other experimental devices: Phoenix body microscope, 3D scanner of Xianlin company.
2.2 | Experimental methods

**Experimental procedures**: (a) pretreatment of rock samples for 12 hours to displace kerosene; (b) measurement of positive permeability $K_0$ of rock samples with kerosene; (c) cyclic contamination of rock samples with drilling fluid for 60 minutes under 3.5 MPa pressure difference on DTSH-III multi-function damage assessment instrument, and measurement of fluid volume; (d) calculation of permeability $K_d$ of rock samples and permeability recovery rate $K_d/K_0$.

**Experimental conditions**: pressure difference 3.5 MPa, shear rate 150 S$^{-1}$, and time 60 minutes. The experimental device has a high-temperature and high-pressure dynamic damage instrument, which can realize a more realistic simulation. At the same time, two cores are tested under the same conditions to ensure the validity of the experiment. Due to the limitation of the number of cores and the purpose of evaluation is core sealing capacity, the same group of cores will be reused in the experiment to ensure the general consistency of fracture morphology, while saving the number of cores, to ensure the overall validity of experimental data.

**Acid solubility test method**: in accordance with China Petroleum Industry Standard SY/T 5358-2010.

3 | RESERVOIR DAMAGE MECHANISM OF OIL-BASED DRILLING FLUID

3.1 | Reservoir protection particularity of oil-based drilling fluid

There are differences between the conclusion of traditional understanding of reservoir protection with oil-based drilling fluid and field practice. Indoor damage evaluation of two kinds of oil-based drilling fluid used in Keshen block of Tarim Oilfield in China is carried out with different density (Table 1). The tests prove that there is great damage in oil-based drilling fluid, which cannot be ignored.

The damage mechanism of oil-based drilling fluids to fractured tight gas reservoirs shows that there is little difference in core damage between oil-based drilling fluids and water-based drilling fluids. However, the formation mechanism of granular blockage damage and the damage caused by liquid phase intrusion are quite different, which are mainly reflected in the following aspects.

1. The process of unstable settlement of solid particles. In general, the suspension stability of solid particles in water-based drilling fluids is good. The migration and accumulation of particles in water-based drilling fluids are more affected by direct forces such as pore throat, fracture or itself. However, oil-based drilling fluid is greatly affected by temperature, pressure, wettability, etc, and the particle suspension problem always exists, which will directly cause the migration and sedimentation of particles.

2. The presence of wettability. The incompatibility between invading fluid and rock wettability directly brings about the problem of wettability. The change of wettability affects the size of intrusive force, the contact relationship between fluid and wall, and the adsorption of particles, which are also the problems that must be considered in oil-based drilling fluid reservoir protection.

3. Oil-based emulsions. The emulsification stability of the oil-based emulsion is mainly maintained by the oil-water interface, which is very vulnerable to the influence of temperature. Thermodynamic instability occurs at high temperatures. This instability leads to a large increase in coalescence and sedimentation rates and may lead to demulsification. Figure 2 experimental results show that with the increase of aging temperature, the damage of oil-based emulsion to the reservoir decreases gradually, but it is still serious as a whole, which cannot be ignored. The main reason for this phenomenon is the thermodynamic instability of oil-based emulsions. It is also shown that the permeability damage caused by oil base drilling fluid is not permanent damage. The higher the temperature, the

| Manufacturer of oil-based drilling fluid | Density (g/cm$^3$) | Core number | Pre-experiment permeability ($10^{-3}$ μm$^2$) | Post-experiment permeability ($10^{-3}$ μm$^2$) | Permeability recovery (%) |
|----------------------------------------|-------------------|-------------|---------------------------------------------|---------------------------------------------|--------------------------|
| Anton Oilfield Services Group           | 1.60              | #1          | 6.5421                                      | 4.1254                                      | 63.06                    |
|                                        | 1.75              | #2          | 7.2547                                      | 4.3107                                      | 59.42                    |
|                                        | 1.90              | #3          | 4.3698                                      | 1.8073                                      | 41.36                    |
|                                        | 2.05              | #4          | 5.6874                                      | 2.1754                                      | 38.25                    |
| SPT Energy Group Inc                   | 1.60              | #5          | 8.2412                                      | 4.8326                                      | 58.64                    |
|                                        | 1.75              | #6          | 7.1687                                      | 3.9686                                      | 55.36                    |
|                                        | 1.90              | #7          | 5.9874                                      | 2.5896                                      | 43.25                    |
|                                        | 2.05              | #8          | 6.3685                                      | 2.5550                                      | 40.12                    |
smaller the emulsion damage caused by oil base drilling fluid. This also indicates that the damage caused by the emulsion itself is not very high at high temperature. However, for the damage that is not eliminated, it mainly comes from the damage of solid particles, which is not affected by temperature. The oil phase and treatment agent of oil-based drilling fluid are the important sources of the non eliminated part of emulsion damage.

4. Multiphase fluid. There are many kinds of liquid phases in oil-based drilling fluids, and it is possible to trap gas to form multiphase flow, which is not similar to the single fluid in water-based drilling fluids. Multiphase flow brings additional flow resistance and further reduces reservoir permeability.21

5. Oil traps. The problem of liquid phase traps is one of the most significant damages to tight sandstone reservoirs. The formation mechanism of water phase traps is in line with that of oil-phase traps, and there are some differences in meso-mechanism. The experimental results (Table 2) of oil traps show that the increase of oil invasion will aggravate the degree of reservoir damage, even in the case of long-term displacement, the permeability damage rate is still close to 50%, and oil invasion causes serious reservoir damage.

Therefore, the protection of oil-based drilling fluid reservoirs in fractured tight gas reservoirs should focus on solving the problems of solid particles caused by rheology and wettability, emulsion stability caused by temperature and pressure, and oil-phase trap of reservoir intrusion fluid.

3.2 | Influencing factors of fractured tight gas reservoir protection for oil-based drilling fluid

The protective effect of oil-based drilling fluid on fractured tight gas reservoir is primarily affected by three aspects: fracture factors, properties of oil-based drilling fluid, properties of reservoir protective materials, and matching relationship with fractures. The mechanism of oil-based drilling fluid on reservoir has been investigated in detail in our previous studies. The following two aspects are basic research on fracture and reservoir protection materials.

3.2.1 | Fracture factors affecting reservoir protection efficiency

Regardless of oil-based drilling fluids, the influence of the liquid phase on fractured reservoirs is considered separately. Factors influencing the protection efficiency of well-entry fluids for fractured reservoirs mainly include the characteristics of fracture itself and the particle size distribution of solid phase particles in liquid phase. It can also serve as divided into five parts: fracture wall roughness, fracture connectivity and filling efficiency, fracture initiation permeability, rigid particle gradation, and flexible particulate matter. Five fracture factors affecting reservoir protection are studied.

1. Surface roughness of fractures

Roughness is a parameter describing the roughness of the fracture wall structure. It grows up to be an important parameter to characterize the permeability of fractures together with the opening degree, filling condition and dip angle of fractures. Figure 3 is a three-dimensional scanning image of the fracture surface, and the fracture surface shows obvious roughness characteristics. The roughness of fracture wall changes dynamically, which is closely related to the seepage process of fracture, the pressure difference in the drilling process, and the

| Initial permeability $(10^{-3} \, \mu m^2)$ | Oil saturation (%) | Gas permeability $(10^{-3} \, \mu m^2)$ | Permeability damage rate (%) |
|------------------------------------------|--------------------|----------------------------------|----------------------------|
| Rock sample: No. R21, Permeability: 0.022 x $10^{-3} \, \mu m^2$ | 63.9812 | 0.006909 | 68.59 |
| 61.1457 | 0.007100 | 67.72 |
| 57.9558 | 0.008375 | 61.93 |
| 55.8784 | 0.008740 | 60.27 |
| 50.4129 | 0.010878 | 50.55 |
technological measures adopted. Various other changes also bring about changes in fracture permeability.

Under formation conditions, besides rock mechanics deformation due to drilling pressure difference, fracture shape and wall micro-convex body distribution will directly affect the migration and accumulation of solid particles in drilling fluid, as well as the invasion distribution of filtrate. Fracture roughness plays an important part in the seepage of drilling fluid in fractures.23,24

2. Fracture connection and filling efficiency

Fractures mostly exist in the form of gridding fracture network in reservoirs. Connectivity between fractures directly affects the oil and gas seepage. If the connectivity between fractures depends on the way of pore and other methods that cannot effectively connect, the oil and gas seepage ability will be greatly reduced, and in most cases, it can only be connected by acid fracturing and other measures.

The filling efficiency of fractures is used to characterize the seepage capacity of fractures filled with filling minerals (Figure 4). Generally, fractures will be filled with filling minerals to vary degrees, and the seepage capacity of fractures after filling may not affect many or may not be able to seepage. Under most conditions, the fracture will be partially filled, which has little effect on the seepage of reservoir, especially gas reservoir, but the filled fracture can offset the stress sensitivity damage caused by partial drilling differential pressure. This is also the reason that some fractured reservoirs have more fracture distribution, but the actual stress sensitivity damage degree of natural fractured cores has not reached a very strong level. Fracture connectivity and filling efficiency determine the percolation ability of oil and gas reservoirs, and also determine the damage degree of drilling fluid to reservoirs. Multiplex connectivity can effectively reduce drilling fluid intrusion blockage and other forms of damage, but it may also cause a large number of filtrate intrusion. Partial filling can not only protect seepage flow, but also reduce stress damage and filter invasion. The damage effect of fractured reservoir can be weakened to some extent by the coexistence of the two parts.

3. Fracture initiation permeability

Permeability is the inherent property of reservoir seepage channel, which is not affected by the measured medium. For fractures, fracture permeability reflects the seepage ability of fractures. Different from the influence parameters of seepage capacity such as roughness, connectivity and filling efficiency, and fracture permeability only represents the size of seepage capacity. The initial permeability of the fracture is the seepage ability of the fracture when it is not invaded and acted by foreign fluid (Table 3). Combined with the analysis of fluid properties, the damage and effect that the fracture may produce can be reflected to a large extent.

3.2.2 | Optimum selection of reservoir protection materials

For fractured reservoirs, the selection of reservoir protection materials is mainly based on field process characteristics and
reservoir protection methods. Under most conditions, reservoir protection materials are the combination of rigid materials and flexible materials. The shape, strength, particle size distribution, surface properties, and chemical solubility of reservoir protection materials will affect the reservoir protection performance of oil-based drilling fluid.

1. Shape and strength factors

For fractured reservoirs, the shape of reservoir protection materials largely determines the efficiency of reservoir protection. Fractured reservoir wall is rough, and mineral filling exists in most cases, which is not a smooth flat fracture.\textsuperscript{25} Shape of reservoir protective particles directly determines the situation of wall action in the fracture. Different from porous reservoirs, the plugging mechanism of two or three particles is not applicable to fractured reservoirs. Under most conditions, the plugging of fractured reservoirs mainly depends on the clamping effect of large-scale rigid particles in fractures or the bridging effect of fiber materials (see Figure 5).

Oil-based drilling fluids also contain particles of various shapes, not only those in Figure 5.

For fractured reservoirs, the bridging strength of particles with different shapes formed between fracture walls is also different. Taking the three types of particles in Figure 3 as an example, elliptical particles have obvious width and fineness, relatively few contact points with fractures, and are easy to flow again under the action of pressure. For bulk particles, the surface appears relatively flat first and is also susceptible to pressure. Compared with elliptical and plugging particles, conical particles are embedded in fractures, so long as the micro-convex body on the fracture surface can withstand external pressure, the bridge structure can be maintained stable.

At the same time, for rigid bridge-erecting particles, the strength of particles themselves is also an important factor affecting the strength of sealing layer of reservoir protection materials (Figure 6). Once bridge-erecting particles are broken, the sealing layer will be affected and broken, and the seepage channel may be re-formed. On the other hand, the strength of fibers is easily neglected. Fibers generally exist in long strips, and clusters are relatively few. Strip fibers bear the pressure transmitted by drilling fluid after building bridges. If the strength is not enough, it is easy to fracture and cause the plugging layer to be destroyed. Drilling fluid once again invades deeper reservoirs.

2. Particle size distribution

Particle size distribution has great influence on reservoir protection ability. Inappropriate distribution of oil-based drilling fluid particles can easily result in low plugging efficiency of near-wall shielding layer. Oil-based drilling fluid filtrate can continuously penetrate deeper reservoirs, causing serious filtrate damage and fine particle pore throat damage.\textsuperscript{26}

| Well     | Layer | Depth (m) | Core type   | Permeability $\left(10^{-3} \mu m^2\right)$ |
|----------|-------|-----------|-------------|--------------------------------------------|
| KS2-2-8  | K1bs3 | 6799-6807.5 | Fractured core | 5.1252                                      |
| K1bs3    | 6799-6807.5 | Fractured core | 24.6895                             |
| K1bs3    | 6799-6807.5 | Matrix core  | 0.0092                          |
| K1bs3    | 6799-6807.5 | Matrix core  | 0.0063                          |
In oil-based drilling fluids, the particle size distribution is determined by the pore size or fracture width of the reservoir. Different particle size distribution will lead to different particle distribution in drilling fluids. Taking the ultra-fine calcium carbonate commonly used in reservoir protection as an example, its size is distributed in the range of several to several thousand meshes. Generally, it is based on the study of reservoir seepage channel size to select. The existing reservoir protective agents are mostly composite plugging agents, which are mixed with a variety of types and granularity distribution of particles, showing better reservoir protection effect.

### 3. Surface properties

For water-based drilling fluids, the properties of reservoir protection materials may be seldom taken into account, but for oil-based drilling fluids, the surface properties of materials must be considered, which is related to both the suspension stability of reservoir protection materials and the stability of oil-based drilling fluids.

Existing conventional reservoir protection materials such as iron carbonate particles, quartz sand, fibers and so on show hydrophilicity (Table 4). If their surface properties are not changed, even if they can be uniformly dispersed in oil-based drilling fluid, they are not easily adsorbed with hydrophilic walls, especially for flexible fibers. The conventional method is to add surfactants to change the surface properties of materials, or directly use surface modified storage materials.

### 4. Chemical solubility

Chemical solubility mainly refers to the acid solubility of reservoir protection materials. In fractured reservoirs, the penetration depth is usually not too deep, and the seepage ability can be restored by natural drainage or perforation. However, for some oil-based drilling fluids invading deeper reservoirs, besides conventional methods, stimulation measures such as acid fracturing are also needed to restore the seepage capacity of fractures. For acid-fractured reservoirs, the acid-soluble effect of reservoir protection materials is particularly important. Based on this situation, acid-soluble materials are often used to plug fractures, but barite, the main weight material of drilling fluid, is insoluble. Even with reservoir protection materials, the effect of acid-soluble materials is still not good. In view of this situation, soluble additives such as micro-manganese ore are used to replace some additives, or micro-manganese ore and other materials are used as reservoir protection materials to protect reservoirs. At the same time, some acid-soluble fiber materials and calcium carbonate were introduced to improve the pickling effect.

For fractured tight gas reservoirs, the plugging layer of fiber or rigid particle bridging does not need to be completely acid dissolved and can form a larger seepage channel. The liquid in the formation will not plug the seepage channel after acid dissolution, and the gas can flow unimpeded to the bottom of the well, as shown in Figures 7 and 8.

Figure 7 shows that the plugging layer formed by fibers has not been completely eliminated after acid dissolution, and there is still a framework of the plugging layer, but it has no effect on gas seepage. Figure 8 shows that there are some insoluble particles left in the granular bridged tight sandstone reservoir after acid dissolution. Without affecting seepage, the granular bridged tight sandstone reservoir can also support fractures and reduce the degree of fracture closure. At the same time, acid dissolution can also remove some temporary plugging particles in the pore and restore the seepage effect of the pore. Therefore, the chemical solubility of materials is an important factor affecting the selection of protective materials for fractured reservoirs.

### 4 | DESIGN METHOD OF RESERVOIR PROTECTION

The main basis for the design of oil-based drilling fluid reservoir protection technology for fractured tight gas layers also comes from the requirements of reservoirs and fluids for reservoir protection. Considering the technology needs of fractured tight gas reservoir, the technology needs to be selected. On this basis, considering the need of oil-based drilling fluid reservoir protection, the technology needs to be further constructed and optimized.

#### 4.1 | Main basis for design

The design of oil-based drilling fluid reservoir protection technology for fractured tight gas reservoirs is mainly based on the requirements of reservoir and fluid for reservoir protection, which is determined by reservoir characteristics and damage mechanism of oil-based drilling fluid. Taking the fractured tight sandstone in Keshen block as an example, the main basis for the research on reservoir protection technology of fractured tight gas reservoir is as follows:
1. The content of sensitive minerals. The content of sensitive minerals has a great influence on the potential damage of reservoirs, and the content decreases with the increase of depth, but it does not satisfy all regions. Taking Keshen block as an example, the absolute content of clay is high, the reservoir has strong water sensitivity, salt sensitivity and alkali sensitivity damage, and strong fracture stress sensitivity damage.6

2. Physical parameters. Reservoirs are defined as tight sandstone gas reservoirs. Generally, the reservoirs show the characteristics of low porosity, low permeability and ultra-low permeability, showing the common characteristics of reservoir damage with low permeability and ultra-low permeability.

3. Characteristics of fractures and micro-fractures. Reservoir seepage mostly relies on fractures and micro-fractures (Figure 9). Drilling fluid is liable to form fracture propagation leakage in smaller fractures and pressure difference leakage in larger fractures. These leakage situations not only cause drilling engineering problems, but also cause greater damage along with reservoir.21

4. Characteristics of pore and throat. For fractured tight gas reservoirs, the pore throat permeability contribution curves of reservoirs are mostly single-peak distribution, and the pore throat interval of permeability contribution is generally less than 0.1 μm. Under the existing technical conditions, micro-nano-particle plugging agent can be used to plug, but the effect is limited.

For fractured tight gas reservoirs, traditional reservoir protection materials cannot effectively plug small pore throats. New micro-nano materials are not suitable for pore throats, but have certain protection effect for larger pore throats. The damage mechanism of fractured reservoirs mainly includes solid phase plugging, filtrate invasion damage and stress sensitivity. The effective hydraulic width of fractures determines the damage degree of fractured tight reservoirs and the leading damage factors. Therefore, the protection of fractured tight gas layers is mainly aimed at fractures and micro-fracture reservoirs, taking into account larger pores, introducing new materials and optimizing protection technology.

Considering the oil-based drilling fluid, it can greatly reduce the damage of sensitive minerals. However, it is necessary to consider the particularity of oil-based drilling fluid reservoir protection and the sensitivity of oil-based drilling fluid in rheology and wettability, so that oil-based drilling fluid can be effectively and uniformly suspended with no
significant fluctuation in rheology, wettability and oil-water interface energy.

4.2 Technical ideas for reservoir protection

From the point of view of the existing reservoir protection technology, the technical ideas of oil-based drilling fluid reservoir protection for fractured reservoirs are mainly cut into the following three aspects: (a) fracture identification. Effective identification of fracture type and opening degree can help us understand the fracture wall morphology and analyze the sensitivity of fractures to operating pressure difference when conditions permit; (b) performance of oil-based drilling fluid. The oil-based drilling fluid used has a preliminary understanding of viscosity, filtration, demulsification, voltage, solid content, etc. The composition and dosage of oil-based drilling fluid treatment agent are relatively clear, so as to ensure the stability of the performance under the condition of adding reservoir protection agent; and (c) engineering requirements. The technological measures adopted in drilling and completion play an important guiding role in the selection of reservoir protection technology.

For the case that fractures and micro-fractures are the main seepage channels, based on the weak to nonacid sensitivity of the Keshen block, corresponding acid pickling or acid fracturing operations are adopted to ensure the smooth flow of seepage channels. For reservoirs with less invasion depth, the damage depth can communicate under natural backflow or within perforation depth. Natural backflow and perforation completion can take acid washing measures to clean the wall of percolation passage and effectively restore the flow efficiency of percolation passage. For reservoirs with large leakage and greater damage depth than perforation depth, acid pickling or acid fracturing is used to destroy the plugging layer and open the seepage passage as far as possible, and granular materials with skeleton function are not considered without affecting seepage.

For lost-circulation reservoirs, because of the need of cementing technology, the sealing zone needs to have high pressure-bearing capacity, which results in repeated plugging of lost-circulation zones to improve the pressure-bearing capacity of the sealing zone. In this process, many times of plugging will cause a large number of drilling fluid intrusion, serious damage to the reservoir. For such reservoirs, it is necessary to ensure high acid-soluble efficiency, but more non-acid-soluble inert substances should also be paid attention to. Ordinary acid fracturing may have very limited effect in the communication of fine seepage channels. Further consideration should be given to the removal of non-acid-soluble inert substances, which is also applied to the technology of non-acid-soluble transformation to improve production, such as barite plugging removal process.

Considering from the above three aspects, combined with the damage mechanism of oil-based drilling fluids to fractured tight gas layers, the technical ideas for protecting oil-based drilling fluid reservoirs in fractured tight gas layers are as follows:

(a) Technology Choice: According to the fracture type, width, possible length and shape, and the particularity of oil-based drilling fluid, combined with the technological measures adopted in the later stage of drilling, the specific reservoir protection methods and technologies are determined; (b) optimized selection of reservoir protection materials: According to the selected technology and method, combined with the possible distribution of reservoir materials in oil-based drilling fluids, the composite scheme of reservoir protection functional materials is determined; (c) constructing reservoir protection technology system: Construct reservoir protection technology systems in existing or newly developed oil-based drilling fluids to evaluate the protection and recovery effects of fracture and micro-fracture seepage capacity.

5 CONSTRUCTION OF RESERVOIR PROTECTION TECHNOLOGY FOR OIL-BASED DRILLING FLUID

According to the investigation and analysis of fractured reservoir protection technology at home and abroad, shielding temporary plugging technology and its derivation technology are effective methods for fractured tight gas reservoir protection. According to the characteristics and damage mechanism of oil-based drilling fluids, the temporary plugging technology is adjusted to be applied in the drilling of different types of oil-based drilling fluids to form a reservoir protection technology suitable for fractured tight gas layers of oil-based drilling fluids.

Shielding temporary plugging technology and its derivative technology can transform pressure difference and original solid particles in oil-based drilling fluid as effective factors, cooperate with reservoir protection agent, form sealing plugging zone with permeability close to zero, and reduce the further invasion of oil-based drilling fluid. Shielding temporary plugging technology is literally temporary plugging. From the application environment, it is mainly aimed at the protection of the reservoir of the open hole section, in order to be able to efficiently and naturally return to the goal of production. But for perforation and other completion methods and drilling-acid fracturing technology, it is enough to ensure fast and efficient plugging effect, and it is not necessary to improve the efficiency of natural backflow. This plugging layer which relies on technology cannot be destroyed naturally. For fractured reservoirs, fracture plugging technology mainly uses bridging particles in drilling fluid to change from
fracture to pore to form porous structure. Further, under the action of reservoir protective agent, combined with the principle of pore plugging and the emulsion nature of oil-based drilling fluid itself, compact mud cake plugging zone can be quickly formed in fractures.

According to the existing literatures, bridging particles in fractured reservoirs can effectively plug fractures when the ratio of size to fracture width is 0.85-1.00.30,31 However, considering the change of fracture ductility and opening degree under stress, this ratio may increase to 0.90-1.00, in order to effectively plug the fractures. For fractured tight gas reservoirs, in the process of drilling with oil-based drilling fluid, it is also necessary to consider how to quickly form dense and high pressure-bearing inner mud cake, reduce the invasion of oil-based drilling fluid filtrate, in order to achieve the purpose of protecting more distant fracture network and matrix pore. The formation of such internal mud cake in oil-based drilling fluid needs to take into account engineering factors, the ratio relationship between flexible and rigid bridging particles and their respective gradations, and the effectiveness of oil-based drilling fluid emulsion components as deformable particles. Taking all factors into account, the mud cake with low porosity and ultra-low porosity can be formed, which can effectively prevent the oil phase from continuing to invade the reservoir.

5.1 Fracture determination and method selection

The first thing to do in fractured reservoir protection is to determine the type and size of fractures.32,33 According to the opening degree, filling degree, validity, angle, and mechanical properties of the fracture, the possible expansion of the fracture is judged. According to the size of the fracture, the possible leakage situation (Figure 10) is predicted. Integrating the properties of the two aspects, the oil-based drilling fluid reservoir protection technology suitable for different sizes and types of fractures is optimized.

According to Figure 10, it can be seen that the main factor causing oil-based drilling fluid to invade reservoirs under conventional conditions is the expansion of natural fractures, which is caused by the pressure difference transmitted by oil-based drilling fluid under most conditions. Based on the understanding of fractured reservoirs, the reservoir protection techniques of different width fractures are roughly classified.

1. For micro-fractures with a width of less than 10 μm, conventional fracture plugging technology is used to protect the reservoir, ultra-fine rigid materials and deformable particles may be used, and the focus is on reducing oil-phase trap damage caused by oil-based drilling fluid intrusion.

2. For micro-fractures with a width of 10-200 μm, conventional fractured reservoir plugging technology is adopted, and ultra-fine fibers, composite ultra-fine rigid materials and deformable particles may be used, with emphasis on reducing oil traps and invasion of ultra-fine particles.

3. For a fracture with a width of 200-500 μm, the interval gradually transits from micro-fractured reservoir to fractured reservoir. Oil-based drilling fluid will enter the reservoir quickly, and the drilling fluid will change from micro-leakage to micro-leakage, which requires a balance between rapid plugging and high-pressure capability. The application of different gradations of fiber materials and rigid materials of different gradations can quickly form inner mud cake sealing zones, and the addition of deformable particles can strengthen the strength of mud cake. The key point of this kind of fractures is to improve the compressive capacity of the sealing zones.

4. For fractures with a width of 500-1000 μm, the leakage of oil-based drilling fluids increases gradually and the invasion depth of oil-based drilling fluids increases. The problems of lost circulation and rapid plugging need to be considered. The initial reservoir protection problem is no longer important in this area. Due to the high pressure-bearing capacity required to form the sealing zone, the network structure constructed by the fiber is not strong enough, and the rigid material of large particles needs to be introduced to form the bridging structure, and the large particles need to have good acid dissolution properties to ensure completion or increase production Effectiveness of measures.

5. For fractures larger than 1000 μm, more consideration should be given to the problem of lost circulation rather than the problem of reservoir protection. In the case of...
controlling lost circulation, the effect of reservoir protection should be taken into account. In this interval, large granular fibers and millimeter fibers are used to block the formation of a high pressure-bearing plugging zone, and then, the porosity of the plugging zone is considered to re-plug, so as to minimize the invasion of oil-based drilling fluid. In this interval, attention should be paid to the compatibility of oil-based drilling fluid with reservoir rocks and fluids, and the expansion or deformation of fractures caused by stress sensitivity should be considered within a certain range, so as to adjust the effective pressure difference of drilling fluid within a reasonable range and avoid multiple damage. At the same time, the acid solubility of the material should be used to reduce the use of inert materials to ensure the effect of acid pressure.

5.2 Differences in engineering requirements

As mentioned above, according to the situation of blocks and adjacent wells, early prediction of later operation measures, whether oil-based drilling fluid is used, and how to break through the sealing zone will put forward different requirements for reservoir protection materials and technology of fractured tight gas reservoirs. According to different confining capacity requirements and different opening modes of sealing zones, fractured reservoir sealing technologies are divided into two categories.

1. Rapid plugging and natural plugging removal

The requirements of this type of plugging are mainly aimed at small micro-fractures, and there is no leakage of oil-based drilling fluids, and the method of natural plugging is used to remove the plugs. The most important requirement of this kind of reservoir is to quickly plug the fractures, form compact mud cake inside and outside, and efficiently remove the plugging, which limits the use of high-damage materials such as fibers, and flexible oil-loving materials such as fibers play a more auxiliary role. Specific reservoir protection materials are suggested as follows:

   Rigid Particles with Different Gradations (Main) + Flexible Fiber Materials (Auxiliary) + Deformable Particles.

2. Rapid plugging and production increase measures for plugging removal

For micro-fractures and fractures with larger openness, oil-based drilling fluid is invaded deeply by drilling pressure difference, which causes serious damage. Natural drainage is not suitable and late measures are needed. For reservoirs that do not require natural plugging, more rapid and thorough plugging with high-pressure capacity is required. Flexible and rigid materials need to be adjusted according to different requirements.

   A Balance of quick plugging and high-pressure capacity

This kind of plugging is mainly aimed at nonleaking large micro-fractures. The technical requirement is to select materials according to perforation and other completion methods or acid fracturing and other technical measures adopted in the later stage to ensure the effectiveness of the measures. For such reservoirs, oil-based drilling fluids may invade a large number of them, but the fracture openness is not high, the differential effect of drilling pressure is not obvious, and the pressure fluctuation of the plugging zone formed is not obvious. It needs oil-based drilling fluids to quickly form internal and external mud cake plugging zone, and cooperate with materials to improve the pressure bearing capacity. Specific reservoir protection materials are suggested as follows:

   Construction of Bridges with Fiber Flexible Materials + Rigid Particles with Different Gradations + Deformable Particles.

   A Highlight high-pressure capacity

This kind of plugging is mainly aimed at the larger micro-fractures and fractures, which are beyond the scope of perforation and other operation modes in technology, and need to adopt acid fracturing and other measures to increase production, so the selection of materials also needs to be adjusted accordingly. For larger micro-fractures and fractures, oil-based drilling fluid leakage will occur in the drilling process. More consideration is given to high-pressure plugging, which can take into account the high efficiency of plugging, so as to prevent oil-based drilling fluid from being disturbed by pressure to destroy the plugging zone and invade the gas reservoir again. Reservoir protection materials are recommended as follows:

   Rigid Particles with Different Gradations (Main) + Flexible Materials with Different Gradations (Auxiliary) + Deformable Particles.

5.3 Particle selection

1. Rigid particles

Rigid particles are usually solid particles with high strength, such as calcium carbonate (Figure 11), quartz sand,
and micromanganese ore. For the requirement of oil-based drilling fluid reservoir protection in fractured tight sandstone, three points should be chosen:

First, the surface wettability of materials. The existing reservoir protection materials are basically surface hydrophilic. For oil-based drilling fluid reservoir protection, the carrier of bearing materials is mainly oil-based drilling fluid, and the surface wettability directly determines the dispersibility of particles in oil-based drilling fluid. In oil-based drilling fluids, the common measures to change the surface wettability of materials are adding wettability or adjusting the amount of asphaltene, which is easily affected by the amount of materials and the properties of oil-based drilling fluids.

Or the method of material surface wetting modification is adopted, which is not affected by the dosage and oil-based drilling fluid, but because of the high cost of the modified particles, the use of the modified particles is limited by the economic reasons.

Second, the strength of the material. In the process of drilling, drilling pressure difference not only promotes the formation of sealing zones by reservoir protection materials in oil-based drilling fluids, but also demands the pressure-bearing capacity of sealing zones, which is reflected in the efficiency of sealing materials and the strength of materials. If the strength of the material is insufficient, the rigid particles will break under high pressure (Figure 11), resulting in the destruction of the sealing zone and the oil-based drilling fluid invading again.

Thirdly, the acid solubility of materials. According to the selection of completion operation measures after formation of plugging zone, acid solubility of materials is also an important selection criterion. Because the amount of reservoir protective materials in oil-based drilling fluid will not be too much, most of the solid particles come from the weighting materials, the existing weighting materials are mostly inert, acid-soluble effect is poor or even not, such as barite. In view of this situation, acid-soluble materials are introduced into weighting materials and reservoir protection materials to ensure the effectiveness of later operation measures. Among the materials used in the field, barite and quartz sand are not acid-soluble, calcium carbonate and micromanganese ore can be acid-soluble, and the acid-soluble effect is good. In Keshen block, micromanganese ore powder and ultra-fine iron carbonate are used to replace part of barite. The acid solubility of micromanganese ore powder is over 99.99%, and the effect is good. Therefore, acid-soluble particles can be introduced into oil-based drilling fluids in fractured tight gas layers to protect the reservoir while heavier.

For calcium carbonate, barite, quartz sand, and other materials, there are many gradations to choose from. Different gradations have a great impact on the rheological properties of oil-based drilling fluid. For example, the viscosities of nano-barite and ordinary barite used in the previous paper are very different. The commonly used calcium carbonate particles are distributed in the range of 5-3000 μm, the conventional quartz sand is distributed in the range of 50-5000 μm, the ordinary barite is distributed in the range of 15-30 μm, the nano-barite is distributed in the range of 1-5 μm, and the micromanganese ore is distributed in the range of 1-5 μm. Small particles will form structural viscosity in oil-based drilling fluids, which will rapidly increase the viscosity of oil-based drilling fluids and affect drilling rate and reservoir protection effect.

There are many kinds of rigid granular materials, some of which are better than conventional ones, but their use is limited by cost reasons. In terms of material selection, some plugging materials while drilling and stopping drilling can achieve full acid dissolution and high efficiency acid dissolution plugging of the lost-circulation plugging zone. For example, crushed waste plastic particles, after screening, have uniform particle size distribution, light weight, and good oil-affinity. Conventional dosage has little effect on rheological properties of oil-based drilling fluid, can be well suspended in oil-based drilling fluid, can also plug fractures well, and has strong pressure-bearing capacity.

2. Flexible fiber materials
Fibrous materials are more commonly used as bridging materials in fractured reservoirs. In addition to rigid strength, there are also problems with rigid materials in rigid particles. In oil-based drilling fluids, the flexible fibers mainly include strip fibers and cluster fibers. There are some differences in the mechanism of action between the two fibers, but the overall effect is not very different. Under certain conditions, cluster fibers may produce high pressure-bearing plugging zones.

Strip fibrous body is a single fibrous body in the conventional concept. It acts with particles to form a bridge between the fracture surface and form a porous structure. Under the action of secondary rigid particles and fibrous body, the pore is blocked and a compact blocking zone is formed. The mechanism of this plugging is to use the flexible deformable characteristics of fibers to plug fractures, but it is precisely because of these deformable characteristics that the pressure-bearing capacity of the fracture plugging zone may be weak when the rigid particles are not well matched. Under the condition of high frequency disturbance of drilling pressure difference, the damage of the plugging zone will occur. Therefore, the sealing of the strip fibers needs to be matched with the rigid particles, and it cannot rely solely on the bridging effect of the strip particles.

Cluster fibers are different from strip fibers. They can trap rigid particles in oil-based drilling fluids and transform them into deformable large particles. In general, the bridge-erecting structure formed by this kind of accumulation has high bearing capacity and can better solve the problem of low bearing capacity of strip fibers. However, under certain conditions, when the cluster fibers are hung by the sharp micro-convex body on the fracture wall to form a bridge, the structure may show a lower compressive capacity, and the stress disturbance may cause them to fall off and continue to migrate.

The existing flexible fiber materials are rich in kinds. According to the needs of oil-based drilling fluids, the surface oil-affinity flexible materials have better dispersibility, which are also derived from surface modification. However, when the viscosity and other properties of oil-based drilling fluids are better, they can also be evenly dispersed into oil-based drilling fluids due to the lighter weight of the fibers themselves and the less amount of the fibers added. For the particle size distribution of fiber-based flexible materials, the length of existing fiber-based materials is distributed in the range of tens of microns to centimeters, and the selection is based on the needs.

3. Deformable particles

Because oil-based drilling fluid itself is an emulsion, it can provide some deformable particles, which is the difference between oil-based drilling fluid and water-based drilling fluid. In some cases, API filtration may increase, and oxidized asphalt, sulphonated asphalt, paraffin, gum, and other materials can be added here to continue to plug the smaller pore on the bridge and further reduce the filtration.

5.4 Fracture sealing and blocking removal mechanism

In principle, the mechanism of fracture plugging is that large particles or fiber bridging—secondary particles and fiber filling—deformable particles plugging micro-holes. In this process, the stability of the bridge-erecting structure is the core factor affecting the plugging efficiency. The high-pressure bridge-erecting particles are required to have sharp edges and corners in appearance, to have good mosaic capacity, or to have good deformability of materials, and to maintain a certain strength.

The particle size of oil-based drilling fluid is distributed in the range of micro-nanometer to nanometer. As described in the mechanism of particle action in the previous paper, the particles in micro-fractures and fractures are migrated and accumulated in the fractures under various forces, resulting in bridging, surface covering and other granular effects. As a seepage channel with high roughness, micro-convex body and nonuniform contact, fractures form bridges at narrower fractures under the action of particle gravity, hydrodynamic force, and adsorption force. This kind of bridge-erecting effect will not succeed in most cases. In a very short period of time, it will break and regenerate repeatedly (as shown in Figure 12). The previous break-up bridge-erecting is not useless. It provides a basis for the next bridge-erecting and ultimately forms a high-strength bridge-erecting structural zone. In the formed bridging structure area, secondary particles and fibrous flexible bodies will continue to invade, forming a secondary structural bridging, so repeated action and filling the porous structural grid, and finally forming a dense plugging area in the crack. The blocked area is often referred to as the inner mud cake.

For fractures, efficient plugging is only the first step, and more importantly, for the plugging zone. According to the different technology, plug removal can be divided into natural backflow without measures, plug removal with perforation and modification. For oil-based drilling fluids, unmeasured
natural backflow is the same as water-based drilling fluids, which are all performed using the pressure difference between the reservoir and the wellbore. For perforation, oil-based drilling fluid has a certain degree of influence from the beginning of cementing to the later operation, which also directly reflects the plug removal efficiency. Firstly, the mud cake formed by oil-based drilling fluid is difficult to remove, and the isolation fluid is required to be high. Moreover, the compatibility between oil-based drilling fluid and water-based cementing fluid is poor, which makes it impossible to achieve efficient cementing. The cement slurry may cause secondary invasion damage. Secondly, the effect of acidizing fluid on the invasion of oil-based drilling fluid and mud cake is not good, or new substances are produced after mixing, which again damages the seepage channel. Both of these problems need to be solved in perforation and plugging removal by later measures. For reservoirs aggravated and plugged by acid-soluble materials, plugging removal by perforation and modification measures is an effective measure to restore the seepage capacity of ultra-deep fractured tight gas reservoirs (Figure 13), which can achieve efficient plugging removal of seepage channels. On the other hand, for inert materials such as barite that cannot be dissolved in acid, the use of barite chelation and deblocking technology can also significantly restore the seepage capacity.

Based on the analysis of fracture determination and method selection, engineering requirement difference, particle selection, fracture plugging and plugging removal mechanism, and combined with design ideas and considerations of reservoir protection of fractured tight gas reservoir, the process of construction of reservoir protection technology of oil-based drilling fluid for fractured tight gas reservoirs established (Figure 12).

5.5 Simulation experiments of oil-based drilling fluid formation protection in fractured tight gas reservoir

Based on the analysis and summary of damage mechanism of oil-based drilling fluid and reservoir protection technology in fractured tight sandstone gas reservoir, physical simulation experiments of oil-based drilling fluid reservoir protection technology in fractured tight sandstone gas reservoir under different fracture conditions were carried out by using dynamic damage experimental device.

5.5.1 Selection of experimental materials

According to the idea of reservoir protection technology construction, the materials involved in the experiment include three types: rigid particles, flexible fibers, and deformable particles. In order to ensure the effect of oil-based drilling fluid reservoir protection and the convenience of material selection, common materials are selected for reservoir protection simulation experiments.

1. Rigid particles

Rigid particles commonly used in reservoir protection include calcium carbonate, lower-mesh quartz sand, and heavier materials. For ultra-fine iron carbonate and quartz sand, it must be selected based on whether the oil-based drilling fluid has sufficient wetting ability; The weighting materials are mainly barite and micromanganese ore. The choice is mainly based on their acid solubility and the ability to form structural viscosity to strengthen the reservoir protection effect. The shape of each particle is shown in Figure 14.

For ultra-fine calcium carbonate and quartz sand, it has the characteristics of low cost, easy to obtain a variety of mesh particles, clear edges and corners in morphology, but the physical properties are quite different. The properties of barite and micromanganese ore have been evaluated in detail in my previous research. The selection of different weighting materials has a great influence on the performance of oil-based drilling fluid. The following is an analysis of the basic properties of several materials to be used in the experiment, as shown in Table 5.

2. Fiber flexible materials

In order to meet the requirements of reservoir protection, a variety of flexible fiber materials are prepared for different situations and applied to different technological measures. The appearance of various fibers is shown in Figure 15. The properties of several fiber flexible materials used in the experiments are analyzed below, as shown in Table 6.

3. Deformable particles

The deformable particles selected in the experiment are modified emulsified asphalt, which can be evenly dispersed when added to oil-based drilling fluid. It can effectively reduce API filtration of oil-based drilling fluid and block micro-pore performance.

4. Damage of particle material

Based on the study of the mechanism of different types of particles in drilling fluids, the degree of influence of different materials on reservoir permeability is studied to provide a reference for the later use of materials. For the same oil-based drilling fluid, different materials of 200 g
are added to evaluate the difference of damage caused by different materials. The experimental data are shown in Table 7.

The experimental data in Table 7 show that the order of damage to reservoir by adding oil-based drilling fluid (formulation of Keshen block) is: flexible fiber materials, rigid particles and deformable particles.

5. Classification of material particle size

In order to facilitate the use of materials in crack plugging experiments, existing materials are graded according to particle size. For different crack widths, the size of the material is divided into rigid particles, and the flexible particles of fiber type have a large distribution range, and the size division is no longer considered; rigid particles only consider calcium carbonate and quartz sand to ensure that the distribution of intervals under different fractures is more reasonable. Among them, barite particles are distributed between 800 and 1500 meshes, and micromanganese ores are distributed between 3000 and 10000 meshes. Except for the case of very small fractures, other rigid materials cannot be considered in this range. The detailed division method is shown in Table 8.
5.5.2 Reservoir protection simulation experiment of oil-based drilling fluid

The fractures in different types and horizons show great differences in width. According to the previous research, there are some differences in protection methods. DTSH-III high-temperature and high-pressure dynamic damage assessment instrument was used to evaluate the difference of reservoir protection in different width fractures. In the experiment, two cores with flat fracture in Keshen block were used to adjust the fracture width by inserting tin foil into the axial edge of the core. Carry out kerosene flooding treatment for two cores for 12 hours for a long time to ensure the consistency of the experimental conditions in the later period. In order to ensure the validity of the experiment, kerosene and fine brush are used to clean the core after each experiment to ensure that the fracture morphology of the experiment is roughly the same.

The method of tinfoil padding is uncontrollable to a certain extent. According to the change of permeability during kerosene displacement treatment, the influence degree of tinfoil padding on permeability is roughly evaluated. Moreover, it is not easy to measure fracture width under the condition of gripper. The equivalent fracture width is calculated by parallel plate theoretical model.\[^{35,36}\]

Parallel plate theoretical model:

\[
W = \sqrt[3]{\frac{3\pi DK_f}{2}}
\]

\(W\), Equivalent fracture width, μm; \(D\), Fracture spacing, mm, 25 mm indoor; \(K_f\), Fracture permeability, \(10^{-3}\) μm\(^2\).

Combined with the existing research results and the classic addition ratio, different arrays of different foil pads were selected to form different crack widths for experiments to evaluate the reservoir protection effect under different ratios of different materials. Because the experiment is carried out in small cores, the drilling fluid leaks rapidly after the fracture is larger than 500 μm, so the further experiment is of
little significance. Combining with the fact that the fracture width of the reservoir is more than 200 μm, the fracture of more than 200 μm is no longer considered.

1. Fractures less than 10 μm

For fractures less than 10 μm, it is suggested that rigid particles and a small amount of deformed particles (oil-based drilling itself is an emulsion, generally not added) be used to plug them, so as to effectively reduce the invasion of drilling fluid. Ultra-fine calcium carbonate was used to plug the fracture, and barite was used to increase the plugging efficiency under the width of the fracture. Table 9 is the experimental data of plugging efficiency with different size of formula particles in oil-based drilling fluid.

The experimental results in Table 9 show that the addition of rigid materials has a great influence on the permeability recovery rate in the small fracture range of 0-10 μm.

### Table 6: Basic properties of fiber flexible materials for experiments

| Material type | Density (g/cm³) | Length distribution (μm) | Acid solubility (%) | Wettability  |
|---------------|----------------|-------------------------|---------------------|-------------|
| CF-2          | 0.88           | 10-127                  | 7.03                | Hydrophilic |
| LHF           | 0.90           | 37-586                  | 89.54               | Hydrophilic |
| OBFM-1        | 0.88           | 300-3000                | 6.21                | Hydrophilic |
| OBFM-3        | 0.91           | 300-3000                | 3.89                | Lipophilic  |
| DTR-2         | 0.90           | <1000                   | 39.58               | Hydrophilic |

### Table 7: Evaluation of reservoir damage degree of different particle materials

| Formula                        | Core number | Pre-experiment permeability (10⁻³ μm²) | Postexperiment permeability (10⁻³ μm²) | Permeability recovery (%) |
|--------------------------------|-------------|----------------------------------------|----------------------------------------|---------------------------|
| Oilfield drilling fluid + 200 g calcium carbonate | R3          | 6.3745                                 | 2.9221                                 | 45.84                     |
| Oilfield drilling fluid + 200 g fiber       | R1-1        | 9.7863                                 | 3.5955                                 | 36.74                     |
| Oilfield drilling fluid + 200 g deformable particles | R6          | 7.5478                                 | 3.9528                                 | 52.37                     |
However, the improved permeability recovery rate has no strong regularity on the whole. This should be based on the wide distribution of materials, and the particle size distribution of each kind is not uniform, which causes similar problems. We can continue to expand the number of experimental groups and observe the trend of subtle changes.

2. 10-200 μm fractures

Perforation completion is often used for fractures with a width of 10-200 μm. It is the first task to ensure rapid reservoir plugging and high pressure-bearing capacity under this completion mode. In the way of plugging, more damaged fibers can be used to build bridges. Combining the bridging and filling of rigid particles, fractures can be quickly plugged, and a small amount of deformable particles can be added when needed. Under some conditions, acid fracturing is also used to increase production. In the experiment, CF-2 fibers were combined with ultra-fine calcium carbonate particles to block, and the permeability recovery rate was evaluated under different particle dosage. The experiment of adding micromanganese ore in the experiment will carry out acid washing to remove plugging. The permeability recovery rate is the fracture permeability after acid dissolution plugging. The experimental data are shown in Table 10.

The experimental results of different fracture widths in Table 10 show that there is no significant difference in permeability recovery between acid-soluble and non-acid-soluble plugging materials. This shows that the damage caused by fracture plugging based on fiber bridging is not easy to remove, and attention should be paid to the optimization of oil-based drilling fluid in the later stage. The experimental results of acid dissolution plugging and acid dissolution plugging without acid dissolution plugging are also quite different, which shows that for the plugging of fiber bridging, the permeability can be quickly restored after the removal of rigid particles plugging, and the skeleton structure of the fiber has a certain degree of damage, but it is not serious. This provides a reference for the selection of process in the later stage.

| Fracture width (μm) | A    | B    | C    | D    | E    | F    | Permeability recovery (%) |
|---------------------|------|------|------|------|------|------|--------------------------|
| 3.57                | 0    | 0    | 0    | 0    | 0    | 0    | 32.59                    |
| 6.84                | 0    | 0    | 0    | 0    | 0    | 0    | 45.21                    |
| 1.67                | 0    | 0    | 0    | 0    | 0    | 0    | 93.24                    |
| 4.68                | 0    | 0    | 0    | 0    | 0    | 0    | 79.53                    |
| 3.56                | 0    | 0    | 0    | 0    | 0    | 0    | 77.45                    |
| 7.48                | 0    | 0    | 0    | 0    | 0    | 0    | 78.47                    |
| 9.21                | 0    | 0    | 0    | 0    | 0    | 0    | 69.26                    |
| 4.56                | 0    | 0    | 0    | 0    | 0    | 0    | 76.35                    |
| 5.87                | 0    | 0    | 0    | 0    | 0    | 0    | 70.23                    |
| 2.53                | 0    | 0    | 0    | 0    | 0    | 0    | 83.61                    |
| 4.25                | 0    | 0    | 0    | 0    | 0    | 0    | 78.54                    |
| 8.87                | 0    | 0    | 0    | 0    | 0    | 0    | 75.61                    |
| 6.25                | 0    | 0    | 0    | 0    | 0    | 0    | 78.54                    |
| 6.45                | 0    | 0    | 0    | 0    | 0    | 0    | 88.68                    |
| 3.19                | 0    | 0    | 0    | 0    | 0    | 0    | 84.62                    |
6 | CONCLUSIONS

1. According to the reservoir protection particularity of oil-based drilling fluid in fractured tight gas reservoirs, the fracture factors affecting reservoir protection, such as roughness, connectivity and filling efficiency, and initial permeability, are defined, and the optimum conditions of reservoir protection materials such as shape, strength, particle size distribution, surface properties, and chemical solubility are established.

2. Based on the influencing factors, the main basis of reservoir protection methods for fractured tight gas reservoirs is clarified. From the point of view of fracture identification, oil-based drilling fluid performance and engineering, combined with the damage mechanism of oil-based drilling fluid to fractured tight gas reservoir, the design idea of oil-based drilling fluid reservoir protection method for fractured tight gas reservoir is formed by considering technology selection and material optimization.

3. Reservoir protection technology for oil-based drilling fluids was constructed from four aspects: determination of fractures, selection of methods, differences in engineering requirements, particle selection, fracture plugging, and plugging mechanism.

4. Based on the formation of reservoir protection technology, the relationship between the amount of reservoir protection material and reservoir protection effect is studied through simulation experiments of oil-based drilling fluid reservoir protection for fractured tight gas reservoirs with fractures of less than 10 and 10-200 μm. The results show that for fractures less than 10 μm, the addition of rigid materials with high mesh number can effectively improve the reservoir protection effect, but the relationship between the amount of materials has little effect. For 10-200 μm fractures, the addition of fibers and rigid materials has little effect on the reservoir protection function without acid dissolution, but the fiber skeleton has less damage to the reservoir after acid dissolution.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
1. Luo Z, Zhang N, Zhao L, Yuan X, Zhang YJP. A novel stimulation strategy for developing tight fractured gas reservoir. *Petroleum*. 2017;4:215-222.
2. Jiang Z, Lin S, Pang X. The comparison of two types of tight sand gas reservoir. *Petrol Geol Exp*. 2006;28:210-214.
3. Lei M, Huang WA, Li N, et al. The damage mechanism of oil-based drilling fluid for tight sandstone gas reservoir and its optimization. *J Petrol Sci Eng*. 2017;158:616-625.
4. Jin L, Wang W. Fractal analysis of tight sandstones using high-pressure mercury intrusion techniques. *J Nat Gas Sci Eng*. 2015;24:185-196.
5. Ballard, Jane, T.J.I.C.L. An experimental study of some mechanisms of damage caused by oil-based drilling fluid filtrate; 1990. Imperial College London. https://spiral.imperial.ac.uk/handle/10044/1/47762.
6. Peng X, Tao Z, Xiao L, Yan Z, Xu M. Damage-control technology of oil-based drilling fluid for Kuqa piedmont structure. *J Geosyst Eng*. 2017;21:1-11.
7. Xu P, Mingbiao X, Zhengwu T, Zhihong W, Huang T. Rheological properties and damage-control mechanism of oil-based drilling fluid with different types of weighting agents. *Roy Soc Open Sci*. 2018;5(7):180358.
8. Zhu J, You L, Li J, et al. Damage evaluation on oil-based drill-in fluids for ultra-deep fractured tight sandstone gas reservoirs. *Nat Gas Industry B*. 2017;4(4):249-255.
9. Li G, Cai W, Meng Y, Wang L, Wang L, Zhang X. Experimental evaluation on the damages of different drilling modes to tight sandstone reservoirs. *Nat Gas Industry B*. 2017;4:256-263.
10. Dabiri A, Afkhami M, Fallah H. Reservoir formation damage due to mud filtration. *Am J Chem Eng*. 2013;1:1.
11. Wilson MJ, Wilson L, Patey I. The influence of individual clay minerals on formation damage of reservoir sandstones: a critical review with some new insights. *Clay Miner*. 2014;49:147-164.
12. Xu C, Kang Y, You Z, Chen M. Review on formation damage mechanisms and processes in shale gas reservoir: known and to be known. *J Nat Gas Sci Eng*. 2016;36:1208-1219.
13. Furuki K, Zhu D, Hill AD. A rigorous formation damage skin factor and reservoir inflow model for a horizontal well. *SPE Prod Facil*. 2003;18:151-157.
14. Reed MG. Formation permeability damage by mica alteration and carbonate dissolution. *J Petrol Technol*. 1977;29:1056-1060.
15. Shu Y, Yan J. Characterization and prevention of formation damage for fractured carbonate reservoir formations with low permeability. *Petrol Sci*. 2008;5:326-333.
16. Farkha S, Khoshnaw FA, Jaf PT. Formation damage removal through acidizing of an oil well after drilling and completion. *Eur Sci J*. 2017;13:154.
17. Fjelde I. Formation damage caused by emulsions during drilling with emulsified drilling fluids. *SPE Dril Complet*. 2009;24:222-228.
18. Kiani M, Saadatabadi AR, Behbahani TJ. Wettability alteration of carbonate rock by nonionic surfactants in water-based drilling fluid. *Int J Environ Sci Technol*. 2018;1-10.
19. Liang T, Gu F, Yao E, et al. Formation damage due to drilling and fracturing fluids and its solution for tight naturally fractured sandstone reservoirs. *Geofluids*. 2017;2017:1-9.
20. Yan J, Menezes JL, Sharma MM. Wettability alteration caused by oil-based muds and mud components. *SPE Dril Complet*. 1993;8:35-44.
21. Xu P, Xu M. Damage mechanism of oil-based drilling fluid flow in seepage channels for fractured tight sandstone gas reservoirs. *Geofluids*. 2019;2019:1-15.
22. Xu P, Pu X, Xiong H, Wang Z. Stability of diesel-oil-based drilling fluid with variable water cut at low temperatures. *Chem Technol Fuels Oils*. 2018;54:195-203.
23. Lanaro F. A random field model for surface roughness and aperture of rock fractures. *Int J Rock Mech Min Sci*. 2000;37:1195-1210.
24. Thompson ME, Brown SR. The effect of anisotropic surface roughness on flow and transport in fractures. *J Geophys Res: Solid Earth*. 1991;96:21923-21932.
25. Madivala B, Vandebrili S, Fransaer J, Vermant J. Exploiting particle shape in solid stabilized emulsions. *Soft Matter*. 2009;5:1717-1727.
26. Zhang JB, Yan JN. Optimization of particle size distribution for temporarily plugging/shielding agents in water base reservoir drilling fluids. *Off Chem*. 2005;22:1-5.
27. Quercia G, Belisario R, Rengifo R. Reduction of erosion rate by particle size distribution (PSD) modification of hematite as weighting agent for oil based drilling fluids. *Wear*. 2009;266:1229-1236.
28. Ye Y, Yan J, Zou S, Wang S, Lu R. A new laboratory method for evaluating formation damage in fractured carbonate reservoirs. *Petrol Sci*. 2008;5:45-51.
29. Wen J, Zhang J, Wang J, Peng S, Huang W, Wang G. Shielding and temporary plugging technology and application in the Biancheng area of north Jiangsu Province. *NGI*. 2006;26:81-83.
30. GuoJ, Liu Y. A comprehensive model for simulating fracturing fluid leakoff in natural fractures. *J Nat Gas Sci Eng*. 2014;21:977-985.
31. Jia L, Chen M, Hou B, Sun Z, Jin Y. Drilling fluid loss model and loss dynamic behavior in fractured formations. *Petrol Explor Dev*. 2014;41:105-112.
32. Wang G, Cao C, Pu X, Zhao Z. Experimental investigation on plugging behavior of granular lost circulation materials in fractured thief zone. *Partic Sci Technol*. 2016;34:392-396.
33. Wang G, Pu X. Discrete element simulation of granular lost circulation material plugging a fracture. *Partic Sci Technol*. 2014;32:112-117.
34. Soares AA, Freitas JCDO, Melo DMA, et al. Cement slurry plugging behavior of granular lost circulation materials in fractured formations. *J Nat Gas Sci Eng*. 2014;21:977-985.
35. Doolin DM, Mauldon M. Fracture permeability normal to bedding. *Fuels and Oils Chem Technol*. 2005;22:1-5.
36. Parsons RW. Permeability of idealized fractured rock. *Soc Petrol Eng J*. 1966;6:126-136.

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