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Research article

A new evaluation method for micro-fracture plugging in high-temperature deep wells and its application: A case study of the Xushen Gas Field, Songliao Basin☆

Liu Yonggui [a,b], Song Tao [b,*], Xu Yongjun [a]

[a] Harbin Institute of Technology, Harbin, Heilongjiang 150001, China

[b] Drilling Engineering Technology Research Institute of CNPC Daqing Oilfield Drilling Engineering Company, Daqing, Heilongjiang 163413, China

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Abstract

Micro-fractures are developed in volcanic layers of Cretaceous Yingcheng Fm in the deep part of Xujiaweizi fault depression, Songliao Basin. In the process of well drilling, various complex problems happen, such as borehole wall slabbing and collapse and serious fluid leakage. Based on conventional drilling fluid plugging evaluation methods, the real situations cannot be presented accurately, especially in fracture feature simulation and plugging effect evaluation. Therefore, a specific micro-fracture plugging evaluation method was put forward especially for high-temperature deep wells in the paper. It is a new type of micro-fracture core model with the fracture apertures in the range of 1−50 μm. It is made of aluminosilicate that is compositionally close to natural rocks. It is good in repeatability with fracture-surface roughness, pore development and fracture-surface morphology close to natural fractures. Obviously, this new model makes up for the deficiencies of the conventional methods. A new micro-fracture plugging evaluation instrument was independently designed with operating temperature of 200 °C and operating pressure of 3.5−5.0 MPa. It can be used to simulate the flow regime of downhole operating fluids, with the advantages of low drilling fluid consumption, convenient operation and low cost. The plugging capacity of the organo-silicone drilling fluid system was evaluated by using this instrument. It is shown that the grain size distribution of the drilling fluid is improved and its anti-collapse capacity is enhanced. Based on the field test in Well XSP-3, the safe drilling problems in volcanic layers with developed micro-fractures are effectively solved by using the drilling fluid formula which is optimized by means of this evaluation method. And the safe drilling is guaranteed in the deep fractured formations in this area.

Keywords: HPHT; Micro-fracture; Plugging experiment; Evaluation method; Drilling fluid; Volcanic rock; Songliao Basin; Xushen Gas Field

As exploration and development activities by the PetroChina Daqing Oilfield Company (hereinafter referred to as Daqing Oilfield) continually go deeper, volcanic gas reservoirs (i.e., the Xushen Gas Field) of the Cretaceous Yingcheng Fm in the deep part of the Xujiaweizi fault depression, Songliao Basin, have became important succeeding resources for the Daqing Oilfield in recent years. As volcanic strata are thick-bedded and broadly distributed in the Xujiaweizi fault depression with numerous fractures and broken zones, complex downhole accidents, such as borehole wall sloughing and collapse and serious lost circulation [1−5], may often occur, leading to huge economic losses in exploration and development [6]. Essentially, after a stratum is drilled, drilling fluids will physically and chemically interact with rocks, pores, fractures and fluids in it, which led to an increase in borehole wall collapse pressure and thus would further increase the risk

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* Corresponding author.
E-mail address: songtao229@163.com (Song T.).
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of wellbore instability, especially in the case of hard and brittle formation with micro-fractures developed at its deeper part. It has been widely acknowledged in the industry that, an important approach to stabilizing the borehole is to prevent the drilling fluids and filtrates from penetrating the formation and to prevent the wellbore [7–9]. Researchers have made great efforts to work out methods for evaluating the micro-fracture plugging. Common methods applied at home and abroad are HPHT filtration loss and dynamic filtration loss, which can provide guidance in porous formation plugging. The modeling of the fractured formation focuses on macroscopic fractures that would induce lost circulation, and the evaluation method for micron-sized fractures is however relatively less studied. The core test method allows for the modeling of formation conditions using a core flow unit, but it involves a complex evaluation process, a lot of repeated tests, and a difficult control of temperature [10–12]. Therefore, it is necessary to develop a simulated plugging evaluation unit with advantages of close morphology to natural micro-fractures, precise fracture aperture, high repeatability and ease of operation, in order to establish an effective method for evaluating the plugging capacity of drilling fluid to micro-fractures and provide technical support for the safe drilling in highly fractured complex strata.

1. Geological setting of deep volcanic rocks

The Xujiaweizi fault depression is a large deep fault depression developed in the northern part of the Songliao Basin, in which the deeply buried Cretaceous Yingcheng Fm strata host well-developed volcanic lithologic traps and are dominated by rhyolite, followed by tuff and breccia. Core data and well log interpretation indicate that, volcanic rocks in this formation mainly contains structural fractures and dissolution fractures with a width of 1–50 μm and a density of 1–5 fractures per meter. Chemical composition analysis, X-ray diffraction, scanning electron microscope (SEM) and casting thin section analysis were performed with volcanic samples from the Yingcheng Fm to determine their chemical composition, mineral type and content, pore structure, and fracture development (Table 1, Figs. 1 and 2) for a targeted research.

SiO_2 is the dominating chemical composition of the Cretaceous Yingcheng Fm volcanic rock (Table 1), followed by Al_2O_3, K_2O+Na_2O, Fe_2O_3, CaO and MgO. Content of clay minerals is low, which are mainly chlorite (with absolute content ranging from 1.99% to 8.06% and relative content ranging from 46% to 72%) and a small amount of illite (with absolute content ranging from 0.29% to 1.60% and relative content ranging from 2% to 8%). Both illite and chlorite exhibit low hydration degree. Volcanic rocks are often tight and hard, and contain mosaic grains and poorly developed and connected pores. These pores are mainly fissure pores with illites attached to the surface and a small amount of locally present cement dissolved pores with few chlorites filled in intergranular pores. Volcanic rocks exhibit textures of porphyritic trachytic, granular, massive, and tuffaceous. Of 22 samples observed microscopically, 20 samples show linear or tubular micro-fractures with a width of 1–50 μm, irregular shapes and varying lengths.

Table 1
Chemical composition of the Yingcheng Fm volcanic rocks.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O+Na_2O
Average content	67.96%	13.52%	1.08%	1.09%	0.63%	8.10%

2. Preparation of a micro-fractured core model and plugging experiments

2.1. Preparation of a micro-fractured core model

In the preparation of a physical model of micro-fractured core that is similar to a volcanic rock formation, a superfine aluminosilicate gelling material, which has close chemical compositions to volcanic rocks and will no longer be hydrated once solidified, was selected in the lab. Chemical compositions are given in Table 2. The micro-fractured core model is prepared in the following procedures. ① Prepare the slurry of gelling material at a certain water-cement ratio and pour it into a core mould. ② Put a metal foil into the gelling material and place them into the water bath for conservation. ③ Remove the foil gently at an appropriate time before initial gelling to make fractures formed with a certain width. ④ Place the mould again in the water bath for conservation and control the final aperture range of micro-fractures by adjusting temperature and time based on a fact that gelling material can resume the hardening (i.e., it can grow).

For comparing the natural core and the micro-fractured core model, a microscopic scanning analysis was performed of micro-fractures in natural core, metal fracture board and core model to determine the fracture surface morphology, using scanning electron microscope and high-resolution full-automatic metalloscope (Fig. 3). In comparison to traditional scanning electron microscope, the use of scientific-grade, high-end, full-automatic DSX500 metalloscope allows for an analysis of a sample without any damage or specific processing. The test is easy to operate, the magnification factor ranges from 139 to 5000, and the resolution can reach up to 0.01 μm, meeting the requirement of a microscopic analysis of rocks. Microscopic analysis indicates that, natural core exhibits a rough surface and contains well-developed pores; metal fracture board has a smooth and flat surface with very few carbonizations, but exhibits a distinctly different fracture surface shape features from natural micro-fractures; and the modeled core, in comparison to the metal fracture board, has irregular textures and well-developed pores, shows a similar fracture shape to the natural core, and is made up of aluminosilicate matrix that is compositionally close to formation rocks.

2.2. Validation of effective micro-fracture width

Effective micro-fracture aperture of core model provides an important parameter for an evaluation test and determines the

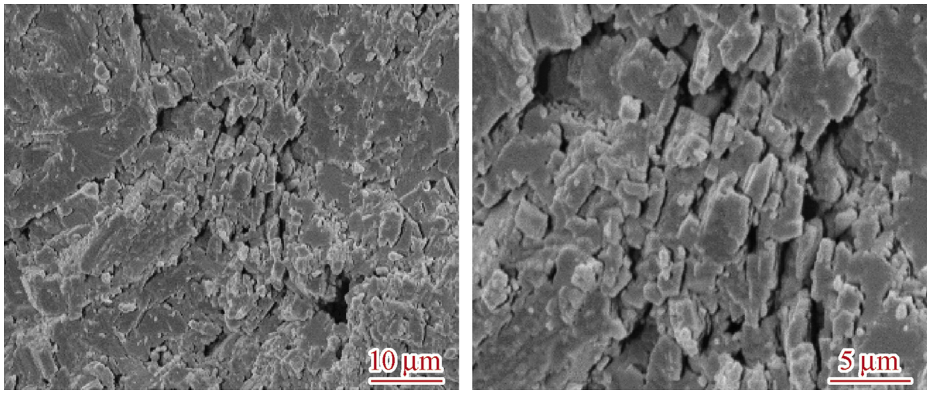


Fig. 1. SEM photos of volcanic rocks.

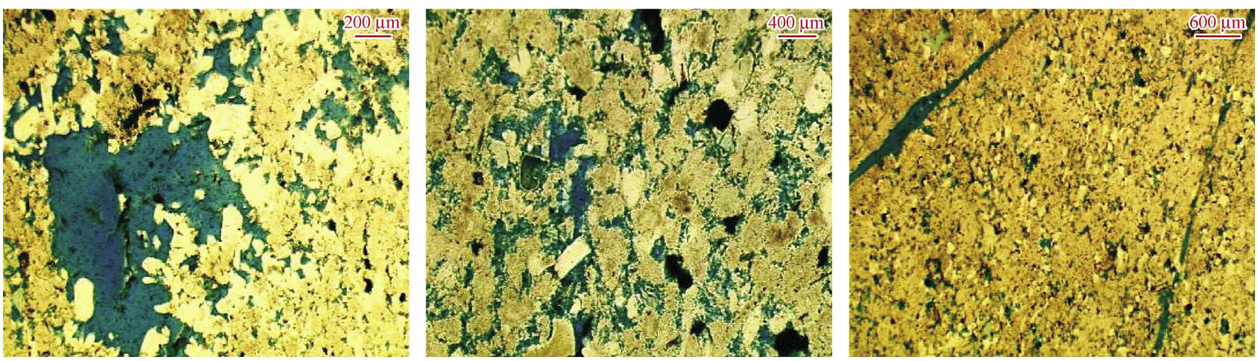


Fig. 2. Casting thin section photos of volcanic rocks.

test accuracy. Based on the mathematical model of the effective width of a fracture in a reservoir [13], the Navier–Stokes (N–S) equation, mass conservation equation and Darcy's Law, an effective aperture model for flow in fracture is derived, as is shown below. This model assumes that freshwater flow medium is a single-phase incompressible steady fluid, and takes into consideration of fracture's fractal features, variation of fracturing degree over different locations and the impact of fracture's surface roughness.

$$h=\sqrt[3]{\frac{12Q\mu L}{\omega\varepsilon\Delta p}}$$

where h is the effective fracture aperture, μm; Q is the fluid flow per unit time in fracture, mL/s; μ is the viscosity of a fluid, mPa.s; L is the fracture length, mm; ω is the fracture width, mm; ε is the correction coefficient for fracture roughness, dimensionless; and Δp is the pressure difference in the direction of fluid flow, MPa.

Based on this mathematic model, a unit for testing the flow through a core was designed and assembled (Fig. 4).

Table 2
Chemical composition of the superfine aluminosilicate gelling material.

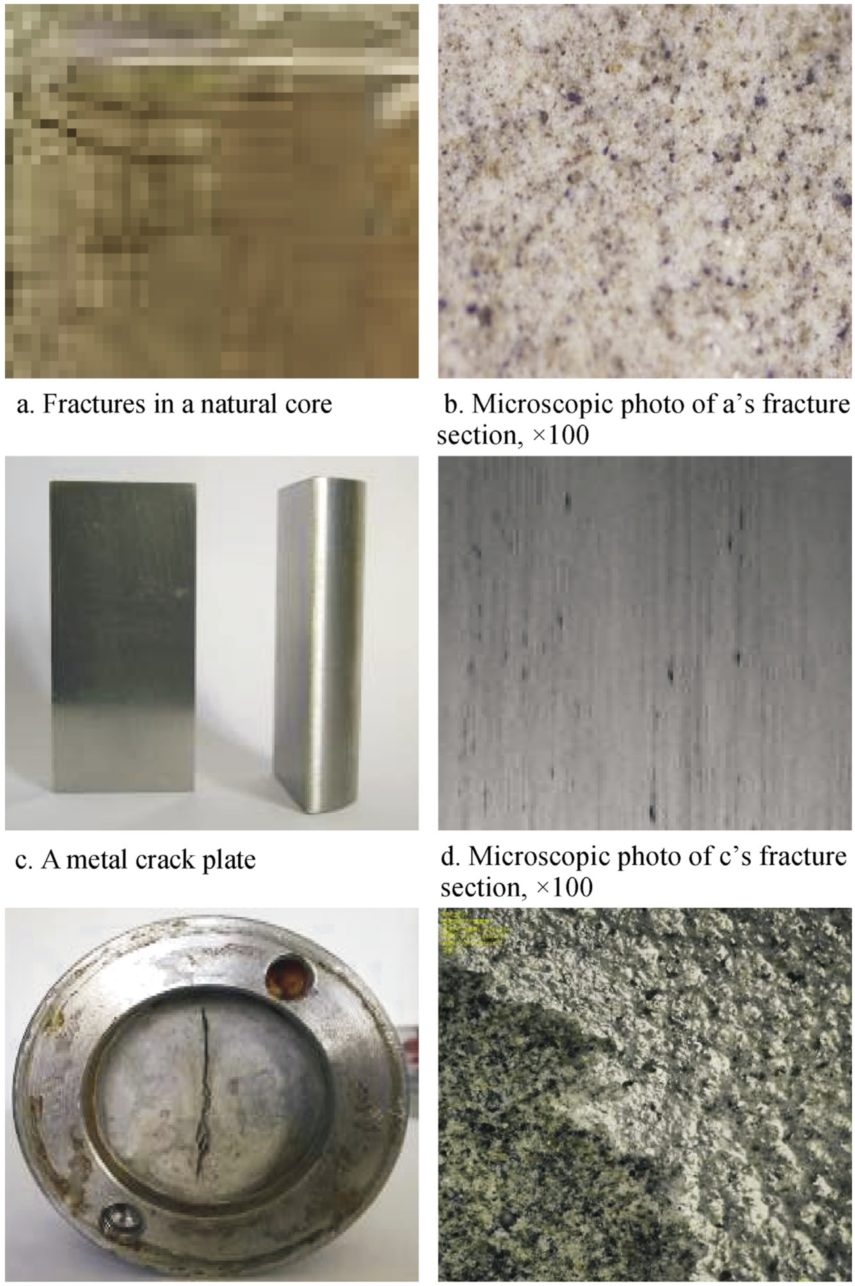
Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O+Na_2O
Average content	52.2%	44.03%	0.65%	0.31%	0.27%	0.83%

Parameters such as the pressure difference at both ends of a core model, fluid flow through the core and fluid viscosity can be measured by a laboratory test to precisely calculate the effective aperture of micro-fracture. In our laboratory test, micro-fractures with widths of 1, 10 and 50 μm were measured for effective flow width. The test results shown in Table 3 indicate that aluminum foils with three different thicknesses reach the design requirement for the aperture of micro-fractures and therefore can be used to model it in formations.

2.3. Structure of the micro-fracture plugging evaluation unit

This micro-fractured core model was used to design a plugging evaluation unit, which is composed of gas source, pressure reducing valve, pressure gauge, drilling fluid cup, upper and lower cup lids, stirring blade, rotating speed control box, heating system, back-pressure condensate receiver, and related sealing elements, as shown in Fig. 5.

As to this micro-fracture modeling evaluation unit, the operating temperature ranges from room temperature to 260 °C, the operating pressure ranges from 0 to 10 MPa, the capacity of drilling fluid cup is 800 ML, the length of micro-fractures ranges from 50 to 100 mm, and the aperture of fracture ranges from 1 to 50 μm. The operating procedures are given below.



a. Fractures in a natural core

b. Microscopic photo of a's fracture section, ×100

c. A metal crack plate

d. Microscopic photo of c's fracture section, ×100

e. A fracture in the modeled core

f. Microscopic photo of e's fracture section, ×100

Fig. 3. Photos of cores and fractures in laboratory tests.

① Prepare the simulated micro-fractured core and install it on a position reserved for the drilling fluid cup.
② Inject the drilling fluid into the cup and cover the lid for sealing.
③ Heat the sealed drilling fluid cup and set the temperature with a temperature control system.
④ After a pre-set temperature was reached, turn on the gas source to simulate the drilling pressure difference and drive the drilling fluid to flow into the micro-fracture under a positive differential pressure.
⑤ Measure the filtration loss at liquid outlet, observe and measure the depth of invasion of the plugged zone into the fracture, and make a comprehensive evaluation of the plugging effect.

2.4. Micro-fracture plugging evaluation test

For enhancing and improving the plugging & anti-collapse capacity, the field-applied organo-silicone drilling fluid was

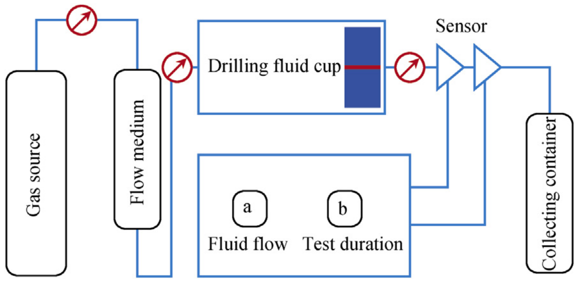


Fig. 4. Schematic diagram showing the structure of the core flow test unit.

Table 3
Measured data for validating the accuracy of fracture aperture with the flow method.

No.	Foil thickness /μm	Measured aperture /μm
1	10	9.83
		8.91
		12.34
2	50	48.30
		55.73
		45.12
3	1	0.89
		2.31
		1.79

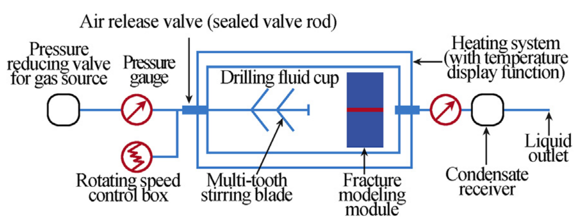


Fig. 5. Schematic diagram showing the structure of the micro-fracture plugging evaluation unit.

evaluated for the distribution of solid-phase particle size and the plugging capacity, using this micro-fracture plugging evaluation unit in combination with a laboratory laser particle sizer.

The particle size of field-applied organo-silicone drilling fluid is measured with a Mastersizer-2000 laser particle sizer (Fig. 6). As shown in Fig. 6, particles with size ranging from 0.4 to 20.0 μm account for about 84.28% of the total volume, and larger particles are relatively less, about 15.72% of the total volume. This suggests the predominance of fine particles in organo-silicone drilling fluid. According to the "1/2–2/3 bridging" law, the plugging of drilling fluid works well on the micro-fractures of less than 10 μm wide. For those wider than 50 μm, however, it fails to achieve an effective plugging because the concentration of particles in drilling fluid is relatively low or mismatches with the width of the micro-fractures.

For validating the analysis results, the designed micro-fracture plugging evaluation unit was used to assess the plugging capacity of the field-applied organo-silicone drilling

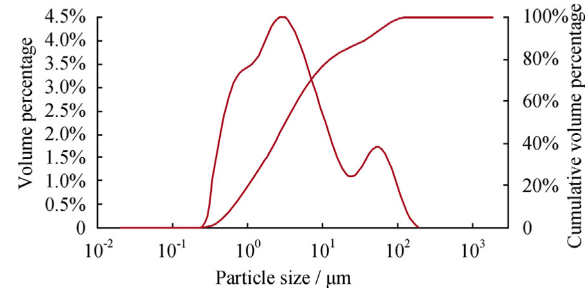


Fig. 6. Distribution of particle size of organo-silicone drilling fluid.

fluid. Plugging of the micro-fractured core model was conducted at 160 °C for 2 h, and the dynamic filtration loss was acquired at the same time. The data obtained from this evaluation test is shown in Fig. 7.

Cumulative liquid output of the drilling fluid used in the plugging test, shown in Fig. 7, increased gradually with time. Fractures in the 1 and 10 μm cases after 40 min tended to reach a steady dynamic filtration loss, which basically no longer increased. This indicates that the drilling fluid exhibits a comparably good plugging capacity when dealing with the micro-fractures of 1–10 μm wide. In the 50 μm case, however, drilling fluid totally penetrated the micro-fracture and then flowed into the metering tube, causing the cumulative liquid output to increase gradually in 2 h. This suggests that the drilling fluid fails to deliver an effective plugging for micro-fractures of 50 μm wide. Therefore, improving the distribution of the size of solid-phase particles in the organo-silicone drilling fluid by adding the plugging particles with an appropriate size into the fluid is required to enhance its plugging capacity.

Particles for plugging, according to the 1/3–2/3 bridging & packing law, should consist of rigid particles for bridging and flexible particles for packing. The size of the selected bridging particles should be 1/3 to 2/3 of the fracture width, and their concentration should exceed 3%. A good plugging effect can be achieved when packing particles have a smaller diameter than bridging particles (about 1/4 of the fracture width) and their content reaches 1.5%. Given the practical situation, a plugging agent named GBW-1 was prepared with ultramicro-fine rigid particles and resin materials by 5% for bridging and packing at the same time.

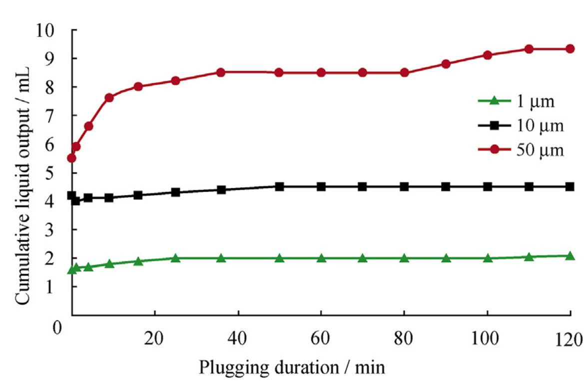


Fig. 7. Cumulative liquid output in micro-fracture plugging test.

Organo-silicone drilling fluid with plugging agent added shows a great change in particle size distribution (Fig. 8). In comparison with the primary system, two peak structures are clearly present on the particle size curve, and the size of particles is mainly distributed in 0.5−10 μm and 20−107 μm, which corresponds well with the size of the bridging and packing particles with 50 μm micro-fractures.

For validating the enhanced plugging capacity of the drilling fluid with plugging agent added, the micro-fracture plugging evaluation unit was used to assess the plugging effect for 1, 10 and 50 μm micro-fractures, respectively (Fig. 9), by observing the dynamic filtration loss and particle accumulation form.

As shown in Fig. 9, after plugging for the 1 and 10 μm micro-fractures, the dynamic filtration loss of the organo-silicone drilling fluid with plugging agent added decreases slightly and then tends to stabilize. This implies a good effect for plugging for the 1 and 10 μm micro-fractures even if the distribution of particle size has changed. After plugging for the 50 μm micro-fractures, drilling fluid exhibits a dramatic decrease in instantaneous liquid output, and then delivers a cumulative liquid output that basically remains stable with time. This indicates that, an effective plugging for 50 μm fracture can be realized by adding plugging agent to drilling fluid, because a plugging zone can be formed at the inlet of fractures to obstruct the entry of drilling fluid (Fig. 10-c). Drilling fluid without plugging agent can totally flow through micro-fractures (Fig. 10-a). A microscopic analysis of micro-fracture section using a metalloscope indicates that, drilling fluid without plugging agent forms loose mud cakes on fracture surface (Fig. 10-b), and adding plugging agent to drilling fluid allows for the formation of tight and continuous plugged zone, as is indicated by the fact that solid-phase particles are scattered throughout the core (Fig. 10-d).

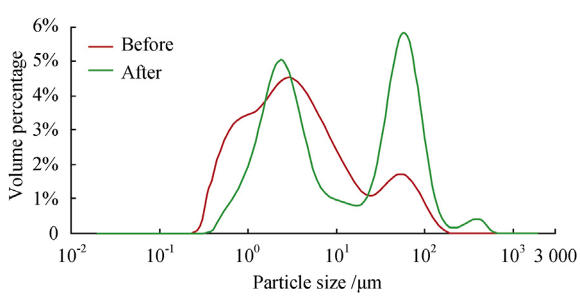


Fig. 8. Distribution of particle size of the organo-silicone drilling fluid before and after plugging agent is added.

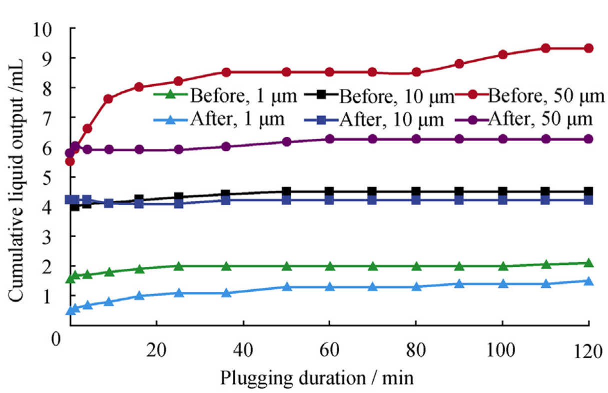


Fig. 9. Curves of dynamic filtration loss of the organic-silicone drilling fluid before and after plugging agent is added.

3. Field application

The plugging agent selected using this micro-fracture plugging evaluation method was applied in Well XSP-3, which is a horizontal well drilled in the Xushen Gas Field. This well, with a designed horizontal section of 1700 m, targets at the volcanic rock of the third member of Cretaceous Yingcheng Formation. This volcanic rock consists of basaltic andesite, volcanic breccia and gray black agglomerate, contains clay minerals, such as illite and chlorite-smectite mixed-layer, and holds well-developed pores and fractures. Since the third-spud to a depth of 3368 m, scrapping and sticking were encountered while the drilling tool was pulled up for reaming, and after reaming to the bottom, drilling tool was pulled up again and then was stuck. Several attempts of repeated reaming were not helpful for this situation and a total of 27 m^3 drilling fluid was lost. Since the drilling cannot be continued, the wellbore was plugged back and sidetracked. Before the drilling fluid entered the target layer, the GBW-1 plugging agent was added to it gradually and repeatedly, and the solid control equipments and sand return at the wellhead were closely monitored. No lost circulation or sticking was observed while drilling in the target layer and the drilling fluid loss per day decreased from 8−9 m^3 to 5−6 m^3. Plugging agent was gradually added to drilling fluid every 100 m interval to ensure a safe drilling, as per the principle of more adding times and a little adding amount. In this way, the 1704 m horizontal section has been successfully drilled with normal return of cuttings, during which problems including the pump pressure jump and lost circulation did not occur.

4. Conclusions

(1) Based on features of micro-fractures in deep volcanic rocks in the Daqing Oilfield, a physical model of micro-fractured core that is made of aluminosilicate material has been prepared. This core model contains micro-fractures with an aperture of 1−50 μm and rough surface, is highly repeatable, holds well-developed pores, and exhibits a fracture-surface morphology close to natural fractures.

(2) The use of this micro-fractured core model allows for an independent design of a micro-fracture plugging evaluation unit, with the operating temperature reaching up to 200 °C and the operating pressure ranging from 3.5 to 5.0 MPa, which provides a simulation of downhole flow stage of drilling fluid. This unit is characterized by low drilling fluid consumption, easy operation and low cost.

(3) This independently designed micro-fracture plugging evaluation unit has been used to assess the organo-silicone drilling fluid and helps to optimize the formula of drilling fluid. Field application indicates that the improved drilling fluid exhibits an enhanced plugging & anti-collapse capacity and provides an effective solution to the challenge that

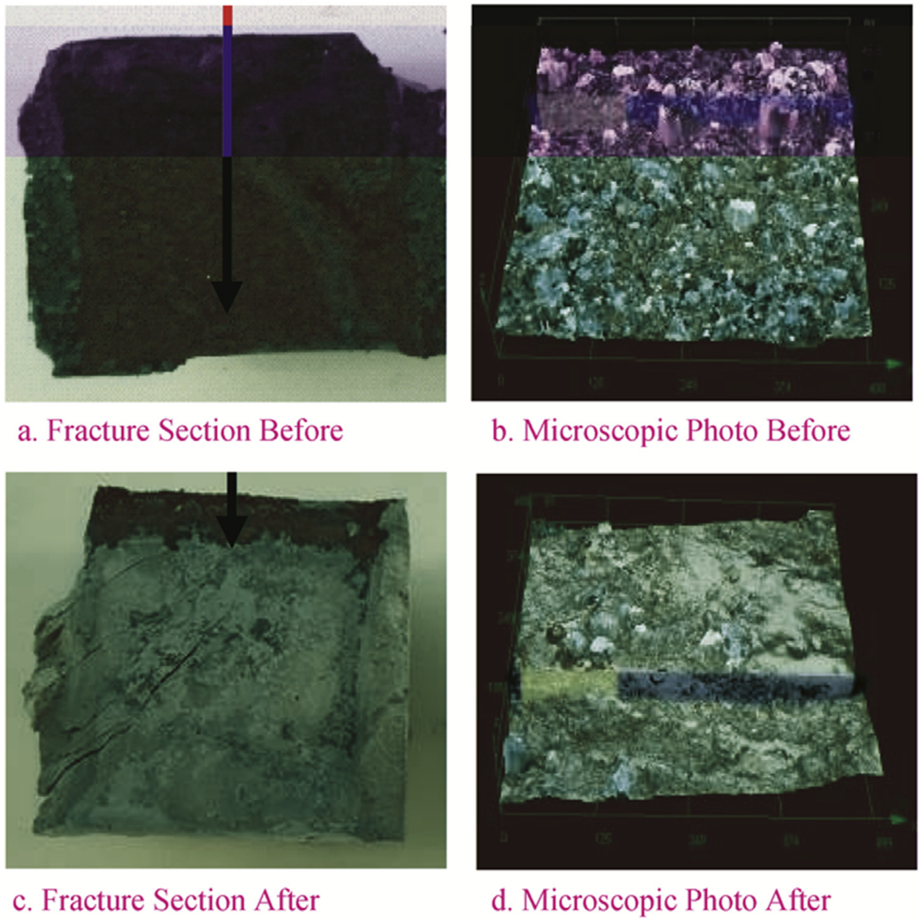


Fig. 10. Fracture section and microscopic photos of the form of 50 μm fracture before and after plugging agent is added.

requires a safe drilling in volcanic rock formation with well-developed micro-fractures.

References

[1] Li Jiaxue. Research on technology of enhancing wellbore resistance capacity by plugging in fracture formation. Chengdu: Southwest Petroleum University; 2011.
[2] Chen Shiyi, Kang Yili, Ma Xuchuan. Application of shielding temporary plugging technology in the new area of East Sichuan. Drill Prod Technol 2005;28(6):10–112.
[3] Liu Jing, Kang Yili, Chen Rui, Liu Dawei, Yang Jian, He Jian. Research status and development trend of damage mechanism and protection technology of carbonate reservoir. Pet Geol Recovery Effic 2006;13(1):99–101.
[4] Xu Zhengshun, Fang Baocai. Characteristics of volcanic gas reservoirs and their development strategies in the Xushen Gas Field, Songliao Basin. Nat Gas Ind 2010;30(12):1–4.
[5] Zhang Chunlu. Classification of petrophysical facies of the volcanic rock in Xushen Gas Field and its application. J Daqing Pet Inst 2009;33(3):18–21.
[6] Kang Yili, Zhang Dujie, You Lijun, Xu Chengyuan, Yu Haifeng. Mechanism and control methods of working fluid damages in fractured tight reservoirs. J Southwest Pet Univ Sci Technol Ed 2015;37(3):77–84.
[7] Jin Yan, Chen Mian. Wellbore stability mechanics. Beijing: Science Press; 2012.
[8] Zhao Feng, Tang Hongming, Meng Yingfeng, Li Gao, Xu Hongming. Study on the influence of microscopic geologic characteristics on wellbore stability of brittle shale. Drill Prod Technol 2007;30(6):16–8.
[9] Gao Mingze. Study on wellbore stability of fractured formation in Xujiaweizi area. Daqing: Daqing Petroleum Institute; 2009.
[10] Zhang Xiwen, Sun Jinsheng, Yang Zhi, Shan Wenjun. Lost circulation control in fractured formations. Drill Fluid Complet Fluid 2010;27(3):29–32.
[11] Yu Weichu, Su Changming, Yan Jienian. High temperature and high pressure dynamic sealing evaluation system. Drill Fluid Complet Fluid 2009;26(1):20–2.
[12] Yu Weichu, Su Changming, Huang Xinran, Zhang Chunyang. Development of the high temperature and high pressure dynamic sealing evaluation system. J Oil Gas Technol 2008;30(5):116–7.
[13] Jiang Haijun, Yan Jienian, Zhang Shiqiang. Effective width model of reservoir fracture. Drill Fluid Complet Fluid 2000;17(2):15–8.