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Enhanced oil recovery mechanism of geological research of tight tuff in Tiaohu formation in Santanghu basin

The permian Tiaohu formation in Santanghu basin is a rare tight tuff oil reservoir containing sedimentary organic matters. With medium-high porosity and ultra-low permeability, the oil reservoir is not connected between wells. In the light of the difficulty in reservoir development, large-scale volumetric fracturing was adopted on horizontal wells. Because of the poor physical properties, however, the fracturing fails to achieve substantial improvement of pore connectivity. The transformation effect is far from desirable, as the high initial production is followed by a rapid decline in yield. In order to effectively develop the tight tuff oil reservoir, the authors analyzed the geological mechanism of tuff tight oil, and adopted the water injection and huff-and-puff (WI-HnP) in the light of lab experiments and field tests. The method maximizes the comprehensive benefits of the exploration and development, and sheds new light on deepening the utilization of tight tuff oil reservoirs.

Keywords: *Tight tuff, Santanghu basin, geological mechanism, water injection and huff-and-puff (WI-HnP).*

1. Introduction

Tight oil is an important unconventional energy resource. Among the various types of tight oil reservoirs, only the tight shale, tight sandstone and tight carbonate reservoirs have been thoroughly researched, while the other types have not received much attention from scholars [1-6]. As one of the unheeded type of oil reservoir, tight tuff reservoirs have been discovered around the world, such as Richland Oil & Gas Field (US), Cristales Oil Field (Cuba), Jatibarang Oil & Gas Field (Indonesia), Samgori Oil Field (Georgia), and Yoshi Kashizaki Gas Field (Japan) [7, 8]. In China, tight tuff reservoirs were detected in Qingxi Sag, Jiuquan basin [9], Jimusaer Sag, Junggar basin [10], Erlian basin [11], and Permian Urho formation, Junggar basin [12]. However, there are afew reports on tight tuffs that contain organic matters. Such a rare case is found in Permian Tiaohu formation, Santanghu basin. The formation is a tight tuff oil reservoir containing sedimentary organic matters.

In 2012, Lu-1 and Ma-55 wells were drilled in the Middle Permian Tiaohu formation of Malang Sag, Santanghu basin, and were proved to be high-yield wells. Then, some old wells were reexamined in the same formation, which also produced lots of oil on a daily basis. The results show that the oil reservoir covers a large area, features continuous distribution, and bears the typical features of tight oil. To further explore the preliminary conclusions, three horizontal wells were deployed successfully in 2013, two of which were subjected to large scale multi-stage hydraulic fracturing. Since then, the tight tuff oil reservoir entered the phase of large-scale development. So far, 70 horizontal wells have been drilled in the study area, and the oil output has accumulated to 298,000 t. Suffice it to say that the tight tuff oil development in Malang Sag, Santanghu basin has been a success.

Much research has been done on the conventional fracturing and exploitation methods of fractured horizontal wells in low permeability tight oil reservoirs [13-18]. In contrast, very little interest has been paid to the tight oil development in volumetric fractured horizontal wells. It was not until recent years that scholars begun to explore the recovery efficiency of tight oil, especially tight tuff oil, in horizontal wells.

The tight oil reservoir has become significant of Santanghu oil field. Nonetheless, the depletion development in the early phase was conducted at the expense of formation energy, resulting in an accelerated decline in production. In order to achieve stable production, it is necessary to further investigate the enhancement of oil recovery. Therefore, this paper probes into the geological mechanism of tight tuff oil, analyzes the geological conditions, and identifies the suitable method of enhanced oil recovery, aiming to maximize the utilization ratio of the oil reserve, and realize comprehensive benefit of exploration and development.

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2. Geological conditions

Santanghu basin is located in the northeastern part of Xinjiang, China, on the southwest of Mongolia, to the east of Junggar basin, and to the north of Turpan-Hami basin. The basin was developed through the tectonic actions of the Kazakhstan plate, the Junggar terraine, the Siberian plate and the Tuha terraine. Since the late Paleozoic era, the region has gone through tectonic movement of the Hercynian period, the Yanshanian period and the Himalayan period. The formation and evolution of the basin are divided into five stages: the formation of the Devonian-Carboniferous basin, the development of the early Permian embryonic basin, the formation and evolution of the late Permian foreland basin, the development of Mesozoic depression basin, and the regeneration of Cenozoic foreland basin [19, 20]. In terms of tectonic unit, the basin consists of the thrust belt [21], the central depression zone and the southern margin of the thrust belt. According to the internal structure and fracture features of the depression zone, the northern and the southwestern areas in the basin are further divided into nine secondary tectonic units.

The study area lies in the Malang depression, which contains the carboniferous, permian, triassic, jurassic and quaternary rock systems. The Permian system is split into Lucaogou formation and Tiaohu formation. Under the effect of the Indosinian movement, the Tiaohu formation developed mixed volcanic and sedimentary facies during the depositional period. The Malang depression comprises three sections. The first and third sections are volcanic rocks of effusive facies, while the second section is volcanic rocks of intermittent lacustrine sedimentary facies. Ranging from 50 to 400m in thickness, Tiaohu formation is widely distributed in the second section. With an average thickness of 150m, the formation contains a 20m-thick tuff layer (Fig.1).

3. Geological mechanism analysis of tight tuff oil reservoir in permian Tiaohu formation, Santanghu basion for water injection and huff-and-puff (WI-HNP)

3.1 Geographical mechanism analysis for the WI-HnP

Starting from the hydrophilic property of reservoir rocks and the water absorption effect of capillary force, the WI-HnP restores formation pressure by injecting water into matrix pores through the suction surface so that the water is stranded in small gaps. Then, part of the water displaces the crude oil in micro pores within the high permeability zone, and part of the water enters and resides in the low permeability channels. Under the gravity differentiation between oil and water, the rock formation is saturated again [22-25].

According to the results of the WI-HnP treatment, the reservoir bears high resemblance to the traditional ones in production features. Combined with the basic theory of water injection in conventional reservoirs, it is further deducted that the tight tuff oil reservoir has a similar water injection mechanism to that in conventional reservoirs [26-27]. On this basis, the author studied the geological mechanism of tuff oil reservoirs for the WI-HnP, performed lab experiment and field test, and proposed an effective method to enhance the tuff oil recovery (Figs.2-5).

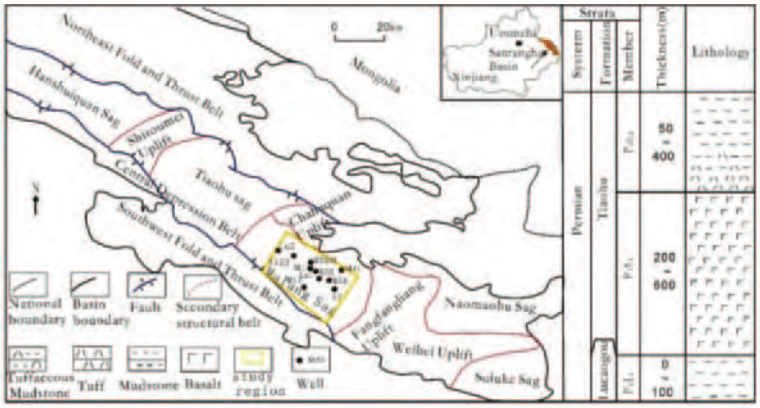

Fig.1 Tectonic division graph and comprehensive stratigraphic columns of the permian Tiaohu formation, Santanghu basin

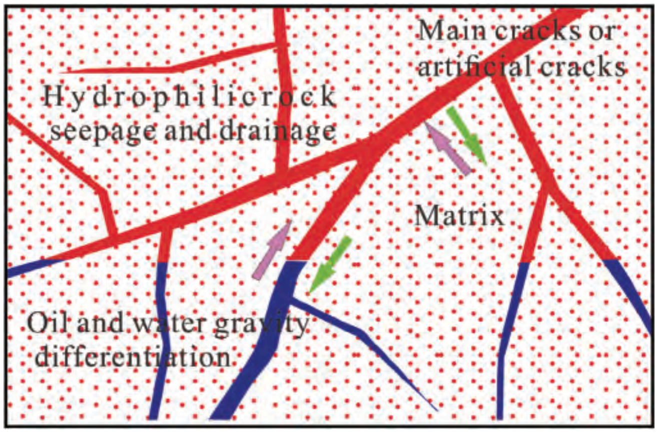

Fig.2 Sketch map of tight oil reservoir

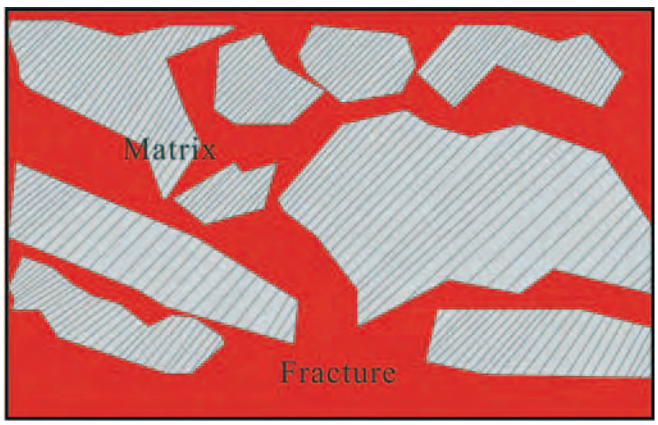

Fig.3 Microscopic sketch map of matrix pores and imbibition-drainage

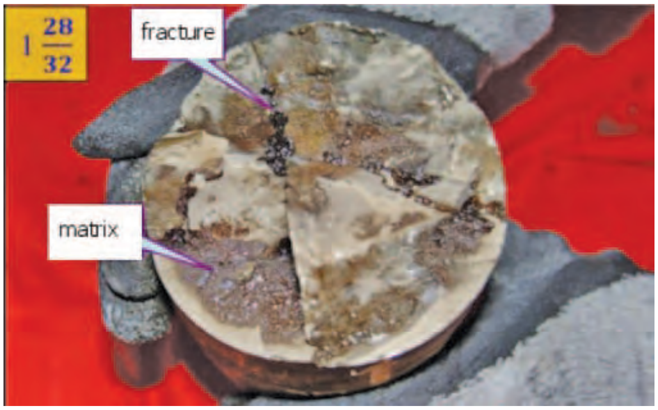

Fig.4 Photo on tuff core in M56-15 well in permian Tiaohu formation

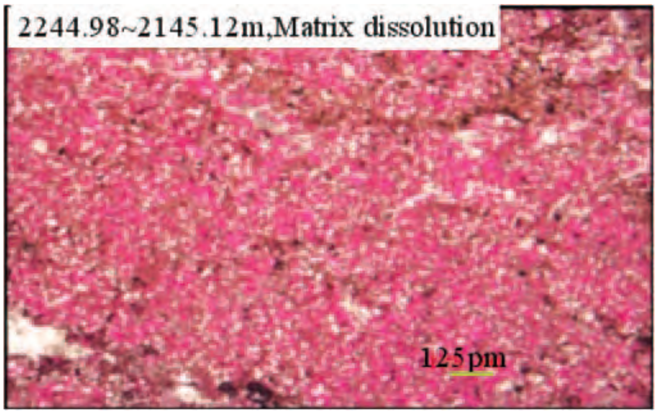

Fig.5. Thin sections of tuff casting in M56-15 well in permian Tiaohu formation

3.2 Geological mechanism analysis of tight tuff oil reservoir for the WI-HnP

According to the theory of Graham, J.W., the influencing factors of oil-water replacement efficiency in the matrix pores include reservoir wettability [28], oil-water contact area, substrate permeability and porosity, crude oil viscosity, oil-water interfacial tension, etc. [29-32]. Coupled with the geological conditions, it is suggested that the following geological mechanism of the tuff in Santanghu basin is suitable for the WI-HnP.

Crack-substrate water displacement:

... (1)

3.2.1 Residual oil

Before applying the WI-HnP in an oilfield, there must be a certain amount of residual oil in the reservoir. In this research, large-scale volumetric fracturing was adopted for the tight oil reservoir on horizontal wells in Tiaohu formation, but the fractures of the wells were not extended to the designed slits, and the reservoir had a certain amount of residual oil. Taking the M56-5H well as an example, the tuff layer was divided into 10 sections, which carried 27 clusters of pores and fractures. The fractured half-seam length was controlled

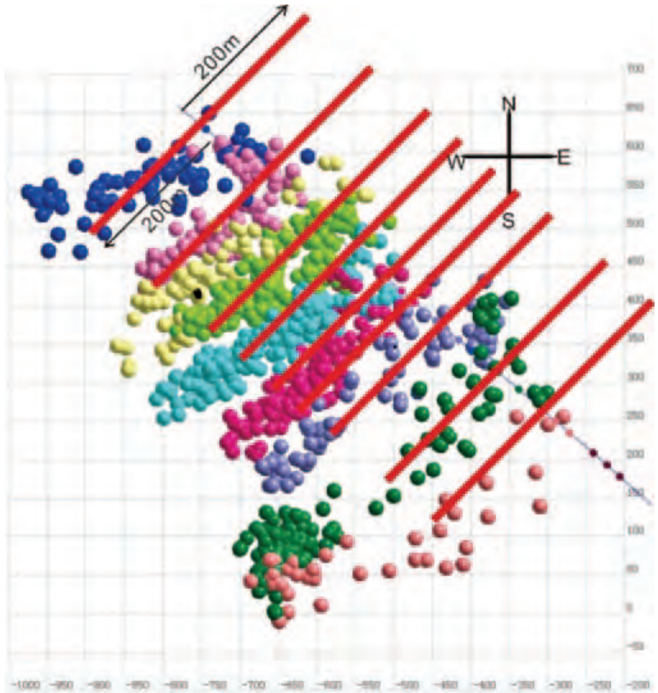

Fig.6 Comparison of designed fracturing cracks and actual fracturing cracks of M56-5H well

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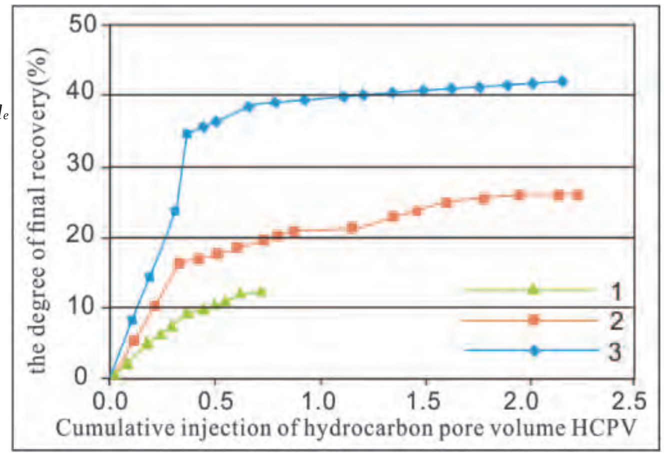


Fig.7 Water injection production curve of tight tuff oil cores with different wettabilities

at 200m. Fig.6 presents the actual micro-seismic monitoring results of the fracturing on M56-5H well, where the red lines stand for the length and direction, and the color points represent the actual pores. It can be seen that the desired fracturing effect is not achieved, and there is still a large amount of residual oil.

3.2.2 Wettability test

Displacement experiments were conducted on different wettability cores. The results demonstrate that the hydrophobicity [33-35] is positively correlated with the final recovery rate (Table 1, Fig.7). If the relative wetting index is 0.71, the recovery rate would reach 41.29%.

In total, 30 samples were tested for wettability, of which 8 were weak hydrophilic and 22 were strong hydrophilic. The core wettability test results reveal that the wettability of the tight tuff oil reservoir changes from weak hydrophilic-hydrophilic to hydrophilic-strong hydrophilic under the action of the fracturing fluid (Figs.8 and 9).

It is concluded that: the more hydrophilic the reservoir, the stronger the ability of seepage and drainage, and the higher the oil replacement efficiency.

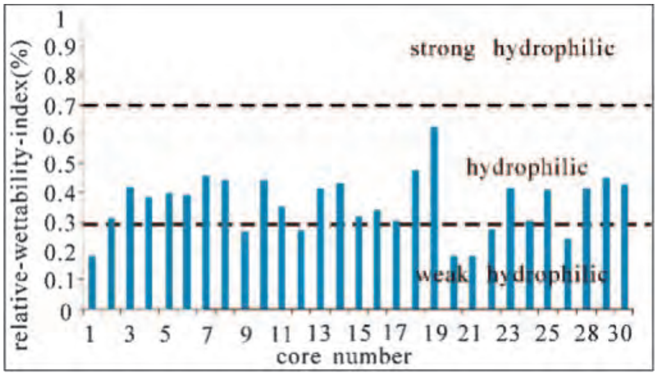


Fig.8 Wettability test of tight tuff oil cores

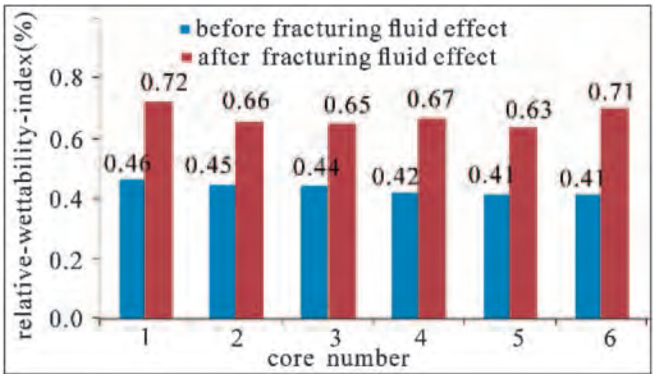


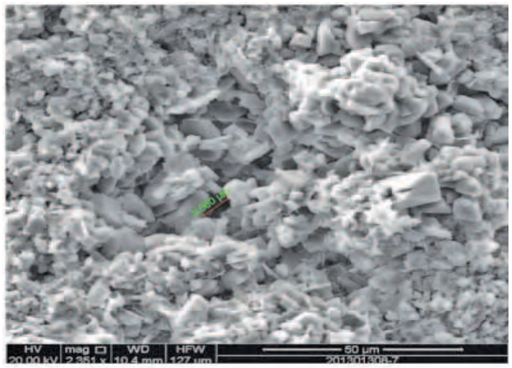
Fig.9 Tight tuff oil wettability before and after fracturing

3.2.3 Development of micro cracks and micro pores

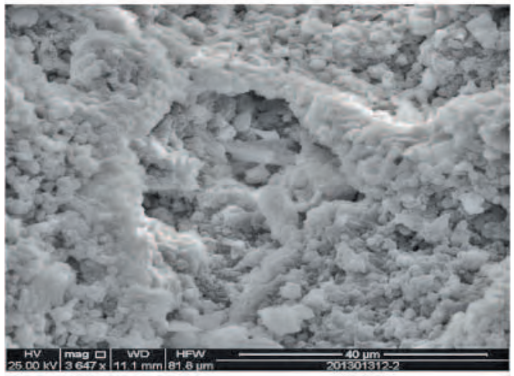
The effect of the WI-HnP is closely related to the development of micro cracks and micro pores. Through the analysis of reservoir features and geographical mechanism it is learned that the micro cracks and micro pores are well developed in the matrix, such as inter-granular mineral pores, intra-granular mineral pores, and organic pores [36, 37] (Fig.10). After the volumetric fracturing, the tuff layer becomes more brittle with a high Young's modulus and a low Poisson ratio. The well-developed fractures widen the oil-water contact, and thus promote transforamtion efficiency. The result is conducive to the WI-HnP.

3.2.4 Physical properties and oil viscosity

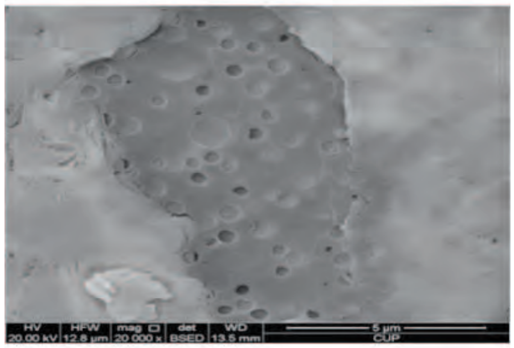
The tight tuff oil reservoir has medium-high porosity and high oil saturation (Table 2). The closer the tuff is to the east, the higher the viscosity of the crude oil, and the lower the



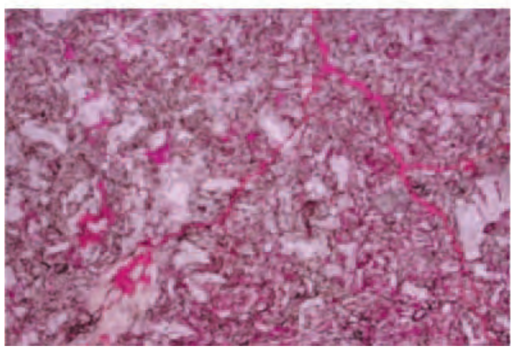
(a) Ma 56 well, 2,144.99-2,145.13 m, porosity is 21%, permeability is 1.77 md, interparticle pores



(b) Ma 56 well, 2,144.76-2,144.82 m; corroded microholes, intraparticle pores



(c) Lu 1 well, 2,548.7 m, organic matter pores



(d) Ma 24 well, casting thin sections, fractures

Fig.10 Types of reservoir tuffs in permian Tiaohu formation, Malang Sag, Santanghu basin

Table 1: The final recovery rate of the WI-HnP for different wettability cores in tight tuff oil

Core number	1	2	3
Relative-wettability-index (%)	0.35	0.48	0.71
Breakthrough volumes HCPV	0.16	0.31	0.36
Break through the degree of recovery (%)	4.45	15.31	33.85
Maximum injection volumes HCPV	0.71	2.24	2.14
The degree of ultimate recovery (%)	11.28	25.2	41.29

Table 2: Tight tuff oil oil and volcanic reservoir physical properties, oil and crude oil viscosity statistics table

Reservoir type	Porosity (%)	Permeability (mD)	Oil saturation (%)	Crude oil viscosity (50ºC, mPa.s)
Tight tuff oil	0.155	0.36	69.1	79.9~4336.0

viscosity of the oilfield. Whereas high viscosity goes against the WI-HnP, the eastern part of the study area is more suitable for implementing the proposed method.

It is concluded that better physical properties of the reservoir brings greater oil saturation, lower crude oil viscosity, and higher oil reservoir transformation efficiency.

3.2.5 Enclosed spaces

Independent closed storage reservoirs prevent the spread of formation energy to the outside world. The formation pressure stimulates capillary water adsorption and oil draining, which, in turn, enhance the formation pressure. The ultra-low permeability tight tuff oil reservoir in Tiaohu formation, Santanghu basin is not connected between wells. In other words, the reservoir range is controlled by single wells. Moreover, most fractured half-seam length did not extend to the designed slit length (Fig.6) after the fracturing. Thus, the reservoir can be regarded as an independent fractured unit [38, 39], which guarantees that the formation energy will not spread to the outside world.

3.2.6 Gravity differentiation

The gravity differentiation causes the water to migrate continuously to the lower part, and the oil to move to the higher part of the seam network. The well trajectory is located in the upper-middle layer of the reservoir, and the effect of the WI-HnP is better than that of the track at the bottom. The horizontal length of M56-13H well is 800m, the drilling rate is 19.4%, and the trajectory is below the oil reservoir. The results show that the WI-HnP has achieved a good effect on the well (Fig.11).

4. Implementation effect of the WI-HNP

Based on the above research, several pilot experiments were successfully conducted on the M55 well in June 2014, to examine the feasibility of the WI-HnP. Later, the WI-HnP experiments were successfully performed on a number of wells. Taking M56-19H well as an example, its oil production was increased from the initial stable value of 20.3 t/d to 3.6 t/d within 18 months. Thus, the WI-HnP method is proved to be effect. When the injected water accumulated to 16,064m^3, the fracturing was carried out with a soak time of 7 days. After the fracturing, the daily production increased to 35.2 t/d, up by nearly 10 times. As of now, the M56-19H has produced 2,736 t more oil. The valid period lasts over 245 days (Fig.12).

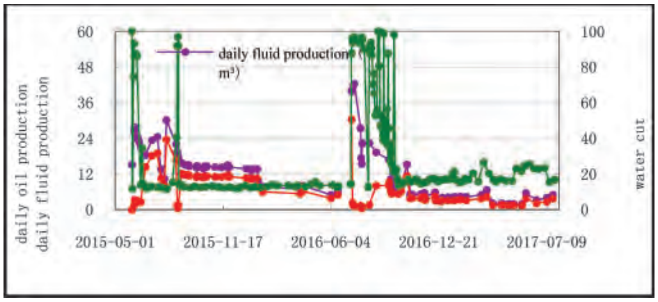


Fig.11 M56-13H well production curve

Up to April 2017, 25 wells in the tight tuff oil reservoir were

Table 3: Summary of the effects of water-flooding huff-and-puff production measures in Malang Sag P2t2 reservoir in Santanghu basin

Reservoir		Tight oil	
Water-flooding huff and puff well numbers		25	
Open well numbers		22	
Statistics		Total	Average
Before water-flooding huff and puff	Daily fluid production (m^3)	88.6	4.0
	Daily oil production (t)	68.9	3.1
After water-flooding huff and puff	Daily fluid production (m^3)	343.3	15.6
	Daily oil production (t)	189.5	9.9
Comparison	Daily fluid production (m^3)	254.7	11.6
	Daily oil production (t)	120.6	6.8
The cumulative increased oil production (t)		12983	649

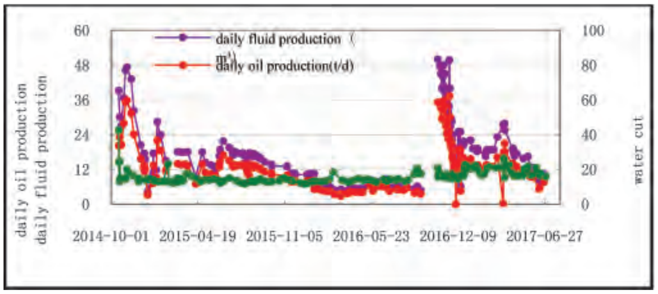


Fig.12 Comparison of production before and after the WI-HnP of Ma 56-27 well

implemented with the WI-HnP. The average single-well product increase reached 6.8 tons/day. This means the WI-HnP has effectively enhanced the recovery of tight tuff oil in Permian Tiaohu formation, Santanghu basin (Table 3).

5. Conclusions

In the Permian Tiaohu formation, Santanghu basin, the factures in tight tuff oil reservoir did not extend to the designed slits, signifying that the reservoir is divided into independent closed parts rather than stretching across different wells. Of course, there is a certain amount of residual oil between the wells. In the meantime, the weak hydrophilic-hydrophilic features of the tuff layer were changed to strong hydrophobicity under the action of the fracturing fluid. The transformation is accompanied with the development of micro cracks and micro pores, leading to strong brittleness and a complex network of fractures. All of the above conditions are favourable for the application of the WI-HnP, which is more effective in low oil viscosity area within the tight tuff oil reservoir with medium-high porosity and high oil saturation. In addition, some well trajectories are located in the upper part of the reservoir, and the water moves continuously to the lower part of the seam network under gravity differentiation, creating a positive condition for the WI-HnP. Based on the above geological mechanism analysis, combined with lab experiments and field tests, it is concluded that the WI-HnP is an effective method to improve the recovery rate of tight tuff oil. This study is of great significance to the geological exploration and development of tight tuff oil in Permian Tiaohu formation, Santanghu basin.

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