

Analysis and Application of the Effect of Controlled Water Fracturing Process in Tight Sandstone Gas Reservoirs

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Abstract

Tight sandstone gas resources are huge, and the complex gas-water relationship for some tight sandstone reservoirs severely restricts the effective development of natural gas. The use of special means to optimize the fracturing process is conducive to controlling water output and improving natural gas production. The previous work on water control fracturing has resulted in a combination of multi-stage sand addition, liquid nitrogen injection and artificial interlayer. The effectiveness of the current water-controlled fracturing process and the influence law of fracturing construction parameters are analysed, the change law of fracture morphology is summarised, and the supporting water-controlled fracturing process is optimised. In this paper, taking a well in a block of Sulige as the research object, the pseudo-three-dimensional fracture morphology model is used to optimise the fracture morphology by improving the stopping time of secondary sand addition, perforation location and construction parameters, and to suppress the high extension of the fracture, thus forming a set of optimised water control fracturing scheme applicable to the reservoir characteristics of this block.

Keywords

Tight Sandstone Gas Reservoir; Water-controlled Fracturing; Fracturing Process; Construction Parameters; Fracture Morphology.

1. Introduction

The Sulige gas field is a complex tight sandstone gas reservoir, and it has been 20 years since its discovery in 2001. The research on reservoir geology, engineering and technology has been continuously carried out around the themes of deepening reservoir understanding, effective development, large-scale development and high-efficiency development, which has become a model for the development of dense gas reservoirs in China [1]. The Su 59 well area is in the western part of the Sulige gas field, and gas-water co-production is a typical feature of the Box 8 gas reservoir [2]. The reservoir rock type is mainly quartz sandstone and rock chip sandstone, and the effective pore space is mainly intra-granular and inter-granular pores. The reservoir pore structure has the characteristics of "small pore throat, poor sorting, high discharge pressure, low continuous phase saturation and small main contribution throat". The physical properties of the reservoir are ultra-low porosity and ultra-low permeability. The gas-water co-layering is mainly related to the inefficient filling of natural gas, the non-homogeneity of the sand body and the late uplift of the structure [3]. With the development of Su 59 block, the physical properties of the reservoir become worse, and the fracturing effect is obviously affected by the water content saturation and the rock mechanics parameters of the compartment. Therefore, it is necessary to analyse the effect of the current water-controlled

fracturing process, analyse the influence law of the fracturing construction parameters, summarise the change law of the fracture morphology, optimise the water-controlled fracturing supporting process, and then form a set of water-controlled fracturing optimisation scheme applicable to the reservoir characteristics.

2. Water control fracturing supporting process

Water-controlled fracturing is divided into two types: "inter-formation water control" and "intra-formation water control". The fracturing process and methods are improved to adjust the fracturing process parameters so that the fracturing extends inside the reservoir and avoids fracturing through the water layer, causing only water to come out of the reservoir, thus achieving increased gas production.

The supporting technology of water-controlled fracturing is relatively mature, and there are many researches on the proppant isolation and construction parameters, etc., but there are few applications in tight sandstone gas reservoirs due to the complex gas-water relationship. In 2013, Bo Cai et al. [4] proposed a turnaround fracture technique to realize the integration of water control and fracturing, and the first results were achieved in the field application. In 2013, Ping He et al [5] applied proppant segment plugging technology, variable displacement fracture control technology, liquid nitrogen injection with energy boosting and discharge technology and phase seepage change technology to field trials in Sulige gas field and achieved better water control fracturing results; In 2013, Huo Zhu et al [6] used the overcoated sand fracturing process to conduct water control fracturing in the Grapevine oil field, and the water content was reduced by 11%; In 2014, Jiarui Li [7] conducted field pilot experiments on selective water control proppant, oil permeable water barrier fracturing fluid, artificial isolation layer and other processes. In 2016, Mingliang Luo et al [8-9] prepared RPM water-control fracturing fluid with polysiloxane and MES as the main additives, analyzed its water-control mechanism, and summarized the reasonable conditions for the formation of nanoemulsions for water control in fracturing tight gas wells; In 2017, Guixian Hao [10] optimized the hydraulic jet fracturing technology according to the reservoir characteristics of Well G82-44-1. After pressure, the oil increased by 7.24t per day and the water cut decreased by 4.7 percentage points, achieving the purpose of oil increasing and water controlling. In 2017, Zhihao Yang [11] used computer language to compile water control selection software for fracturing sections of horizontal wells in bottom water reservoirs, and its practical application showed that it has a certain guiding effect on field construction; In 2019, In 2019, Feng Xingwu [12] studied the change of oil-water permeability characteristics of formation by fracturing water plugging agent in the law of factors affecting the height of artificial fractures, and formed the technology of thin interlayer controlling the height of artificial fractures; In 2020 Zhao Jun et al [13] conducted water-controlled fracturing in fractured dense sandstone of Sulige gas field using plugging vesicular fluid, and the average daily production of a single well was increased by about 10%.

The fracturing techniques used in tight gas reservoirs include multi-stage sand addition, liquid nitrogen injection and artificial interlayer [14].

2.1. Multi-stage sand addition process

Multi-stage sand addition is to add the designed total sand volume to the reservoir through reasonable multiple pumping, stop pumping after the first stage of fracturing, wait for the proppant to settle and the fracture to close, then proceed to the next stage of fracturing, laying down the fracture step by step. During the fracturing process, firstly, pump the pre-fluid and low-viscosity mixed sand fluid in low displacement to form a sand dike in the near-well fracture, then instantly increase the pumping displacement. At the same time, under the premise of ensuring no sand plugging, gradually increase the sand ratio until the reservoir is fully transformed. For the sand bodies with the same layer of gas and water, most of them show the

characteristics of upper gas and lower water, without mud shale barrier, the use of multi-stage sand addition process can have control over the high extension of the fracture and avoid excessive communication with high water-bearing formations [15].

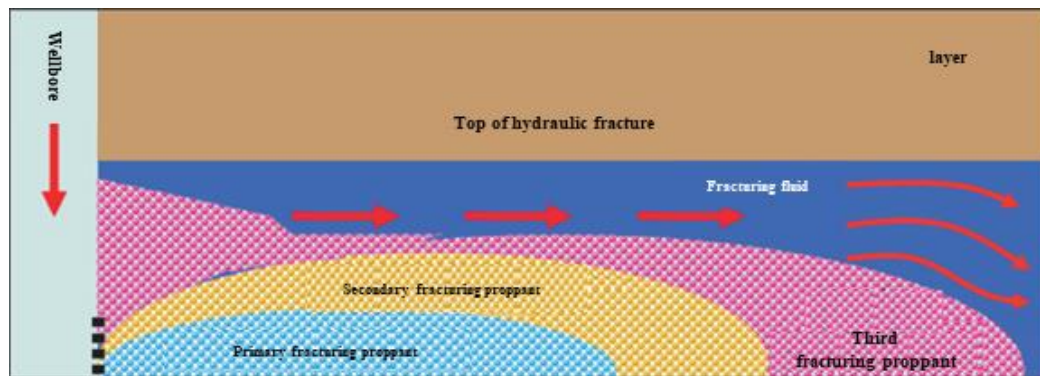


Fig. 1 Schematic diagram of the multi-stage sand addition process

2.2. Liquid nitrogen injection process

The use of liquid nitrogen energy boosting and discharging process for sand fracturing is equivalent to injecting a section of high-pressure gas cushion into the formation fracture, which can not only reduce the fracturing fluid filtration damage, but also provide a certain amount of high-pressure nitrogen energy for post-fracturing re-discharge, effectively compensating for the lack of formation re-discharge energy, which can significantly improve the re-discharge rate of low-pressure oil and gas wells, reduce reservoir damage and improve the effect of sand fracturing [16]. The liquid nitrogen injection process is often combined with fracture forced closure technology, using fracturing fluid rejection model calculations, indicating that the lower the formation permeability, the longer the fracture closure time [17].

Table 1. Fracture closure time at different permeability

Permeability K(mD)	Closing time t(min)
0.3	116
1	108
5	97

The physical properties of the reservoir in Su 59 block are characterised by extra-low porosity and extra-low permeability, and the liquid nitrogen injection process can be used to increase the rejection rate, improve the proppant sand laying pattern and form a gas-water percolation channel with high inflow capacity.

2.3. Manual spacer process

In fracturing construction, if the barrier layer has poor shielding ability, the fracture will pass through the barrier, and the aquifer will also cause a sharp rise in water content if it is close to the production layer, affecting the fracturing effect and even causing fracturing failure [18].

Pumped low-viscosity fracturing fluid carries high-density quartz sand and gel, which settles to the bottom of the fracture to form a low-permeability artificial barrier and inhibit fracture extension along the fracture height.[18-19]

When hydraulic fracturing is carried out in reservoirs with the same gas-water layer in tight sandstone, proppant of different density and small particle size is used to control the fracture height extension. On the one hand, the fracture can be prevented from extending in the high aquifer, which can effectively improve the fracturing area according to the principle of material

balance. On the other hand, the artificial isolation layer formed by using small particle size and high mesh proppant is low permeability and low porosity layer, which delays the water breakthrough time of gas well..

3. Effectiveness of water-controlled fracturing process

Combined with the above-mentioned water control fracturing techniques, a multi-stage sand addition, liquid nitrogen injection and artificial interlayer were combined to form a water control fracturing scheme. The sand section of Well A was fractured from 3540 to 3562m and the reservoir properties are shown in Table 2. The sand section is a low-permeability, low-porosity reservoir, and from the logging interpretation results, the reservoir is adjacent to the water layer and there is no obvious compartment, so it is a gas-water homogenous layer. The construction parameters in Table 3 are used

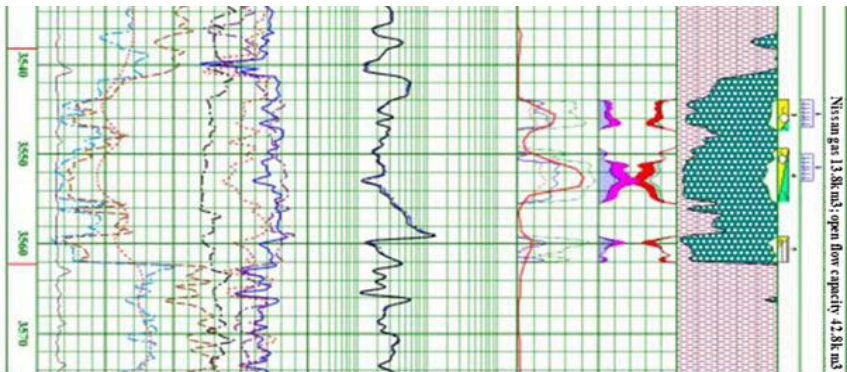


Fig. 2 A well production layer log chart

Table 2. Table of reservoir log interpretation results for Well A

Well section (m)	Thickness (m)	Porosity (%)	Permeability (mD)	Water content saturation (%)	Explanation of conclusions
3507.9 - 3511.2	3.3	6.7	0.1	97.4	Gas-bearing aquifers
3543.8 - 3547.4	3.6	6.6	0.1	73.7	Gas-bearing aquifers
3549.3 - 3555.4	6.1	9.2	0.2	67.0	Aerated water layer
3559.2-3562.0	2.8	5.8	0.1	84.3	Aeration Zone

Table 3. Table of fracturing construction parameters for well A

Pre-liquid ratio	Net liquid volume (m³)	Sand volume (m³)	Volume of liquid nitrogen (m³)	Displacement (m³/min)	Perforation section (m)
40.1	198.5	12.5	13.1	2.3 - 2.5	3550-3553

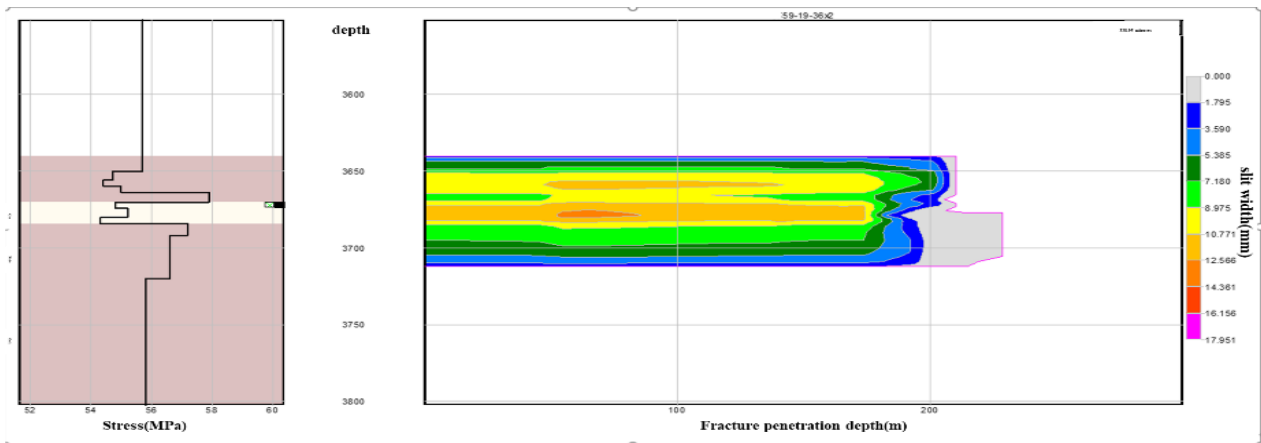


Fig. 3 Fig. A well fracture pattern

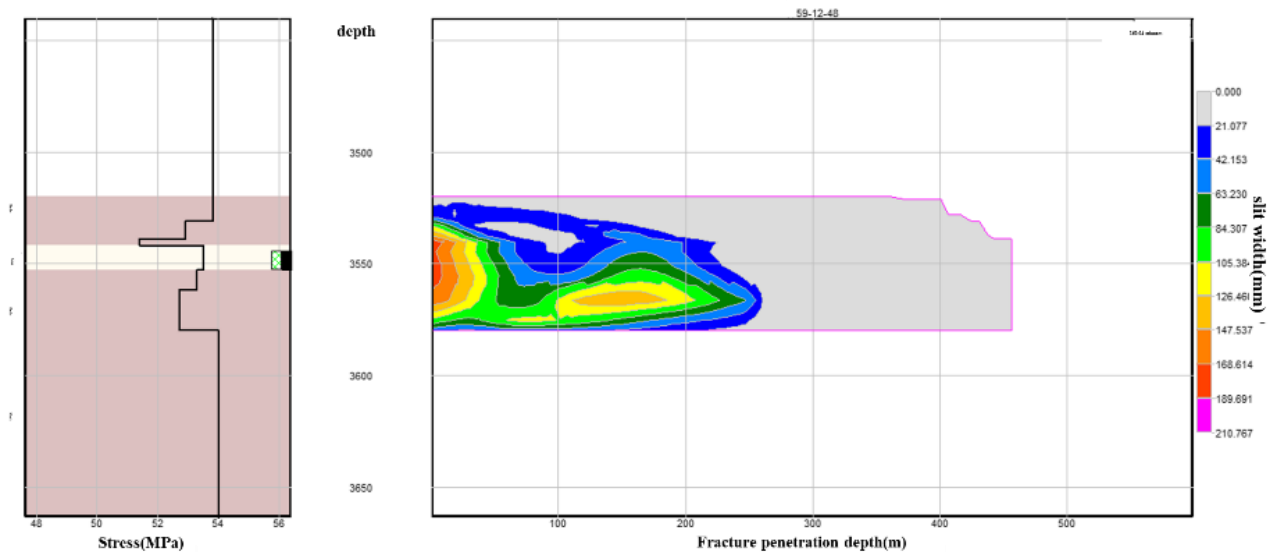


Fig. 4 Map of fracture support inflow capacity in well A

The gas production of well A has increased after compression, but the water production is high, with a daily gas production of $1.38 \times 10^4 \text{ m}^3/\text{d}$ and a daily water production of $28.8 \text{ m}^3/\text{d}$, indicating that the transport of formation water cannot be effectively suppressed. Therefore, simulations of fracture extension were carried out using the simplan software, and the resulting fracture pattern is as follows, which, when compared with the logging curve, indicates that hydraulic fracturing has pressed through the water layer.

4. Optimization of fracturing process parameters

Combined with the above fracturing construction parameters of Well A, the water-controlled fracturing technology plan still has room for improvement. The fracture morphology can be optimized and the fracture height extension can be inhibited by improving the pump stop time, perforation position and construction parameters of secondary sand feeding. In this paper, the fracture geometry was calculated using a proposed three-dimensional fracture pattern model. Palmer assumes that the formation is homogeneous, the oil layer and the capping layer have the same modulus of elasticity E and Poisson's ratio γ . The vertical profile of the fracture is always elliptical; the stress difference between the oil layer and the capping layer is equal; and the flow within the fracture is laminar. The geometry of the three-dimensional fracture is shown in the figure:

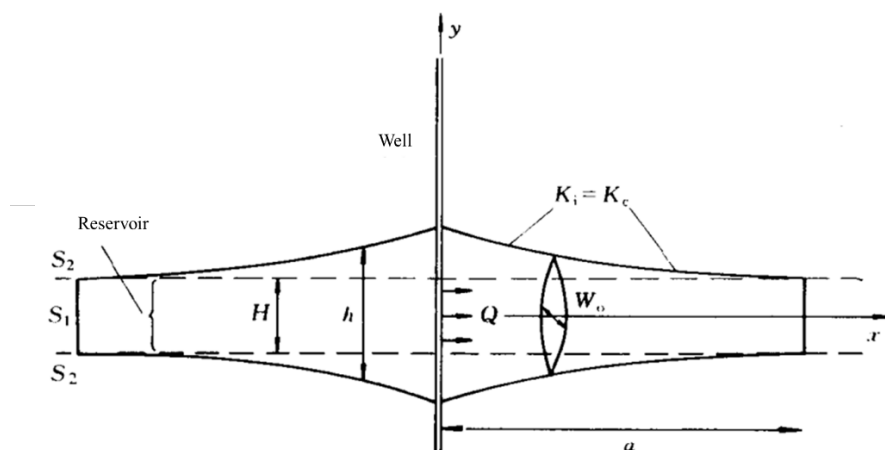


Fig. 5 Geometry of the quasi three dimensional fracture

The fracture width of a quasi three dimensional fracture corresponds to the fracture width obtained by the two-dimensional calculation method in the vertical direction at each point along the fracture length. The fracture width W_x is therefore necessarily a function of the net pressure P_x , the fracture height $H(x)$ [21].

$$W_{fe} = \frac{4(1-\nu^2)}{\pi E} H(x) \int_{f_l}^1 \frac{f_2 df_2}{\sqrt{f_2^2 - f_l^2}} \int_0^{f_2} \frac{p(f_1) df_1}{\sqrt{f_2^2 - f_l^2}} \quad (1)$$

The fracture morphology simulation was carried out to address factors that have a significant impact on fracture morphology in the current water-controlled fracturing scenario, including pumping discharge, sand addition, net fluid volume and pumping downtime.

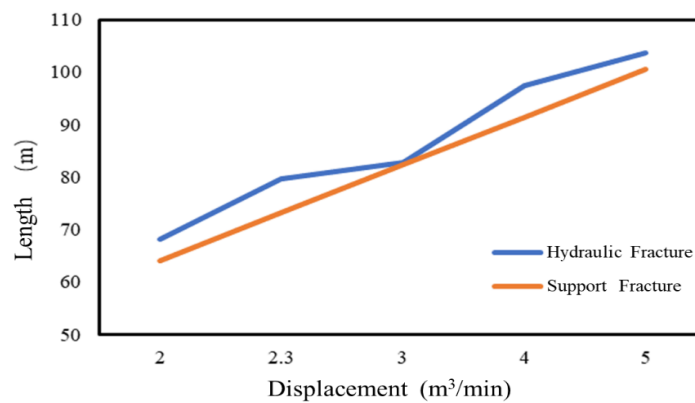


Fig. 6 Variation of fracture pattern at different displacements

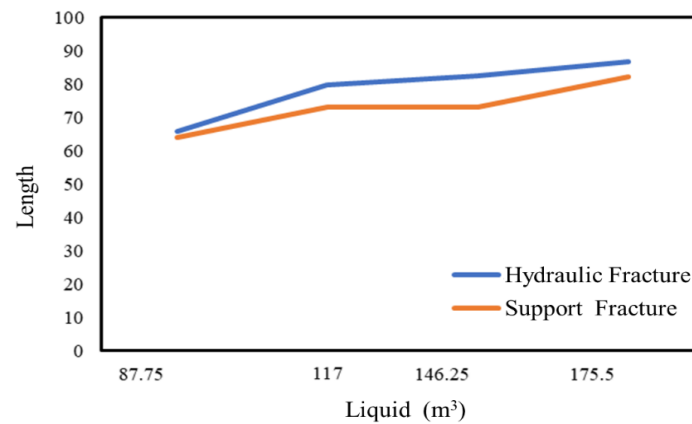


Fig. 7 Variation of fracture morphology for different net fluid volumes

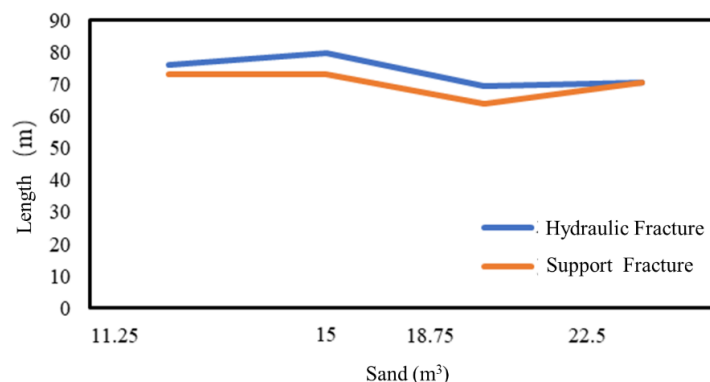


Fig. 8 Variation of fracture morphology for different sand volumes

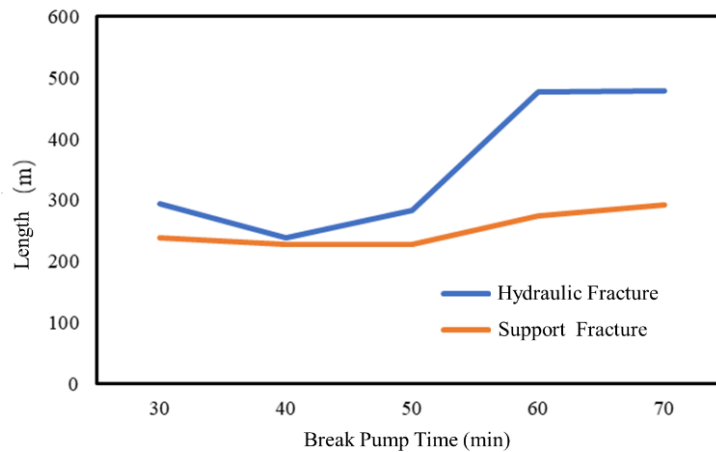


Fig. 9 Variation of fracture morphology for different pump stopping times

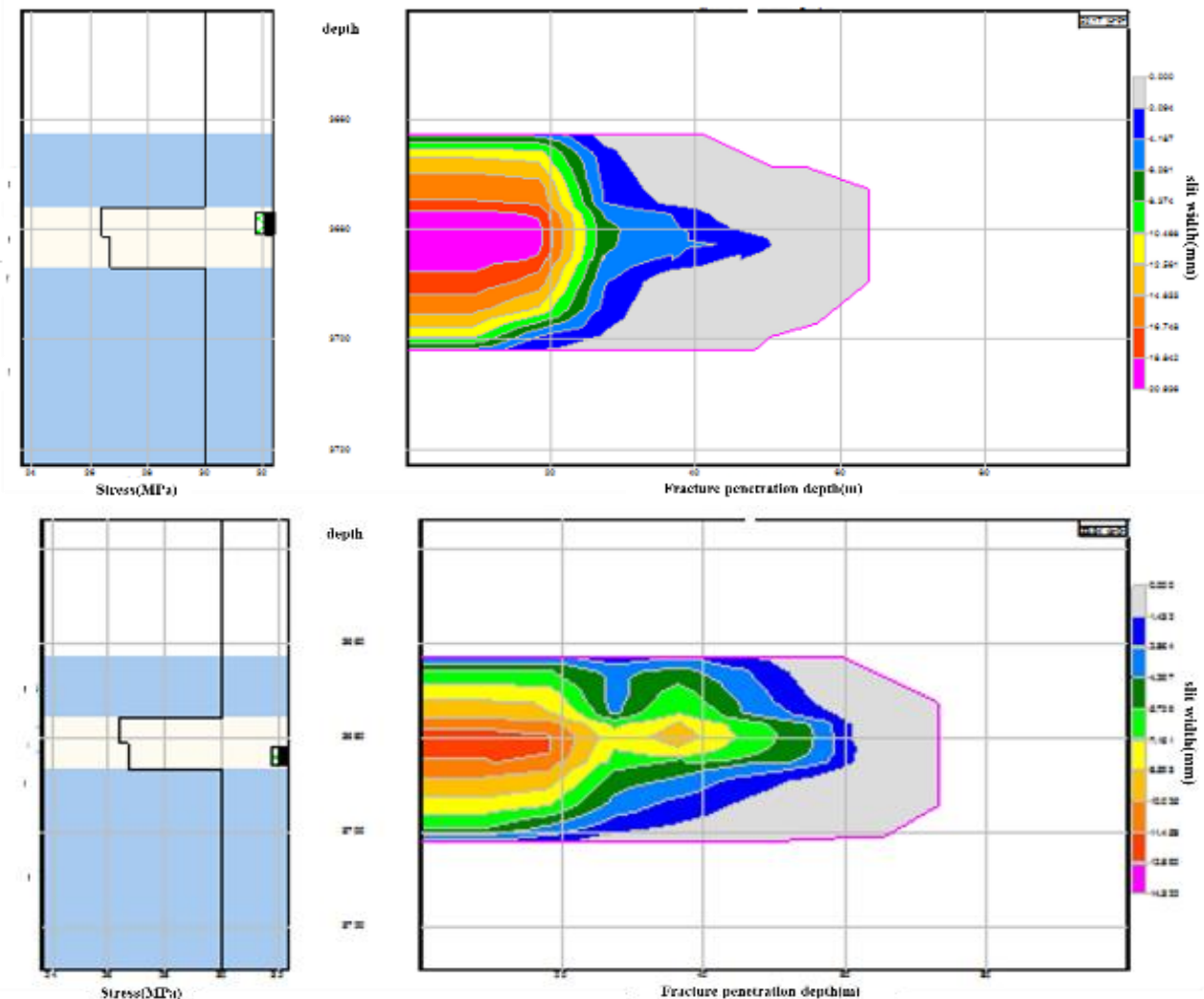


Fig. 10 Variation of fracture morphology at different shot hole locations

As shown in Fig.6-10, the fracture length increased as the pumping displacement and net liquid volume increased. As the fracture closes, the hydraulic fracture becomes a support fracture, where at a discharge volume of 3 m³/min, the hydraulic fracture is basically the same as the support fracture. The sand addition volume has no effect on the change of fracture length, while the stopping time in the multi-stage sand addition process has an obvious effect on the

hydraulic fracture morphology, with the increase of the stopping time, the hydraulic fracture length shows a trend of first decreasing and then increasing, among which at 40min pump stopping time, the length of the hydraulic fracture and the supporting fracture are basically the same. It can be seen that, targeted optimisation should be carried out for different reservoir characteristics, such as the horizontal principal stress of the reservoir compartment, rock mechanical parameters, reservoir physical properties, and the location of the adjacent water layer.

5. Application of optimized water-controlled fracturing process

Based on the analysis of the influencing factors of water-controlled fracturing technology, sand interval 3667-3692 of a single well (Well B) was selected for fracturing. The reservoir properties were referred to the log interpretation results in Table 4, in which the average porosity of the gas-water formation was 11.3%, the average permeability was 0.33mD and the average water content saturation was 75.5%. In contrast, the gas-bearing formation has a water saturation of 96.6% and is not significantly spaced from the gas-water formation.

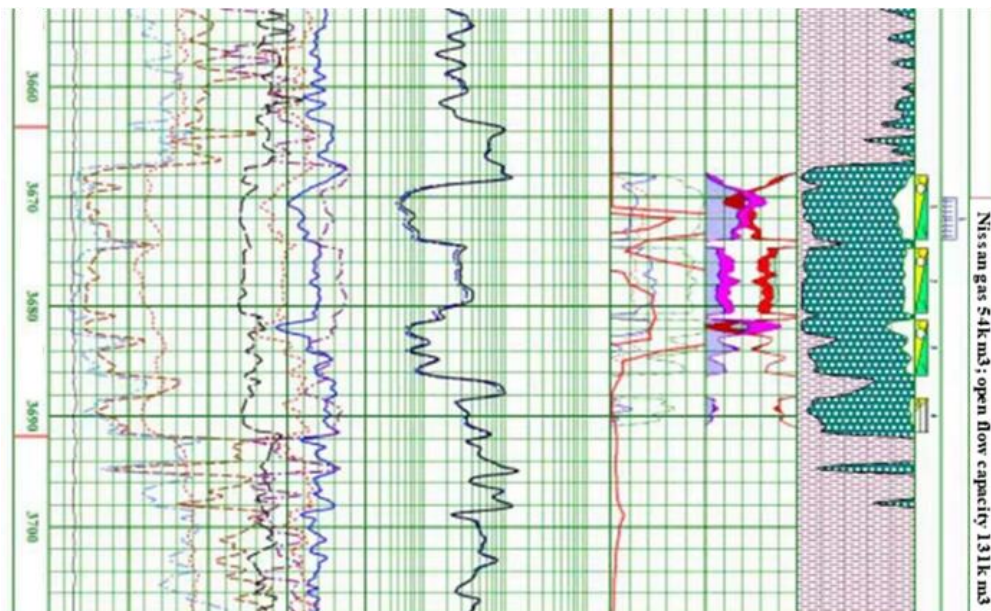


Fig. 11 Well B production formation log chart

Table 4. Table of well B log interpretation results

Well section (m)	Thickness (m)	Porosity (%)	Permeability (mD)	Water content saturation (%)	Explanation of conclusions
3668.0 - 3673.9	5.9	13.2	0.4	77.0	Gas-Water Formation
3674.7 - 3680.6	5.9	9.8	0.2	60.9	Gas-Water Formation
3681.2 - 3686.3	5.1	10.9	0.4	88.6	Gas-Water Formation
3688.3-3691.5	3.2	3.5	0.04	96.6	Gas formation

According to the reservoir rock mechanics parameters and the physical characteristics of the reservoir compartment, the fracturing construction parameters were optimized, and the perforation in the upper part of the reservoir is finally determined, with the perforation section of 3670-3674m, the pumping main displacement of 5m³/min, the net fluid volume of 563.2m³, the sand volume of 60 m³, the pre-fluid percentage of 37.9%, the stopping time of 50min, and the pumping procedure as shown in the table. The construction curve is shown in the graph, and the fracturing is normal. After forced fracture closure, the well produced 5.4 x 10⁴ m³/d of gas and 6.3 m³/d of water after fracturing, with an unobstructed flow rate of 131.08 m³/d.

Table 5. Table of pumping procedures for well B

Serial number	Net liquid volume m ³	Phase sand liquid volume m ³	Displacement m ³ /min	Sand concentration kg/m ³	Phase sand volume m ³	Liquid Nitrogen Displacement L/min	Remarks
1	25	25.0	3~5	0	0.0	160	100 mesh powdered sand
2	15	15.5	3~5	80	0.8	160	
3	18	19.1	3~5	160	1.8	160	
4	22	23.9	3~5	220	3.0	160	
6	25	27.7	3~5	280	4.4	160	
7	35.8	35.8	3~5	0	0.0	0	40/70 mesh Quartz sand
8	114	114.0	3~5	0	0.0	160	
9	20	20.8	3~5	100	1.3	160	
10	27	29.3	3~5	220	3.7	160	
11	33	36.8	3~5	300	6.2	160	
12	37	42.4	3~5	380	8.8	160	20/40 mesh Laminated quartz sand
13	39	45.6	3~5	440	10.7	160	
14	34	40.5	3~5	500	10.6	160	
15	26	31.4	3~5	540	8.8	160	
16	35.8	35.8	3~5	0	0.0	0	

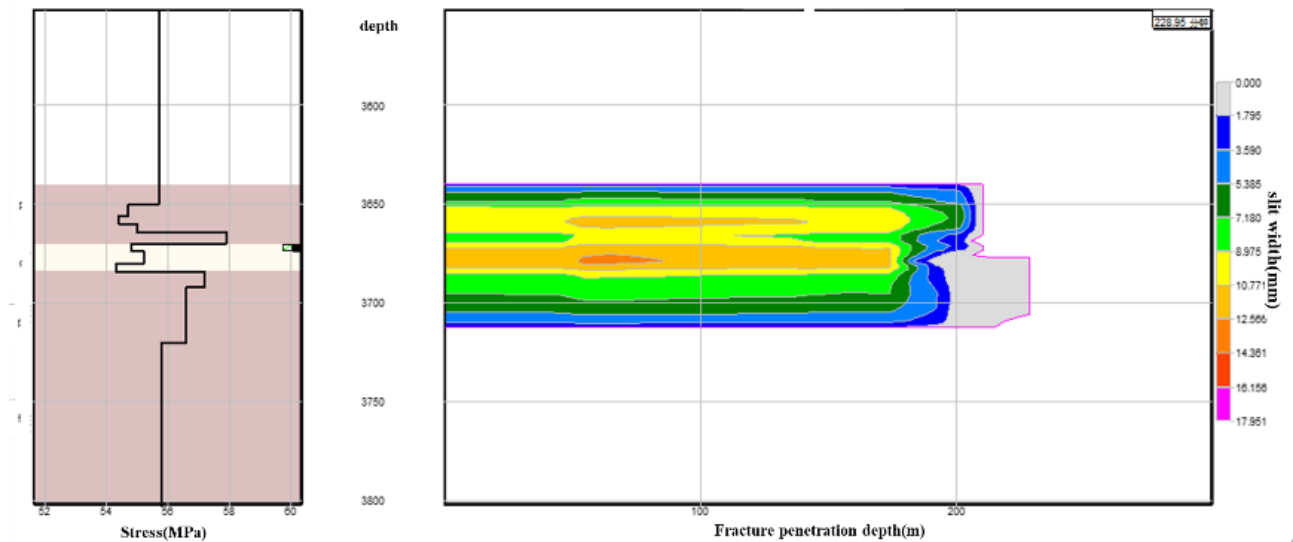


Fig. 12 Fracture pattern in well B

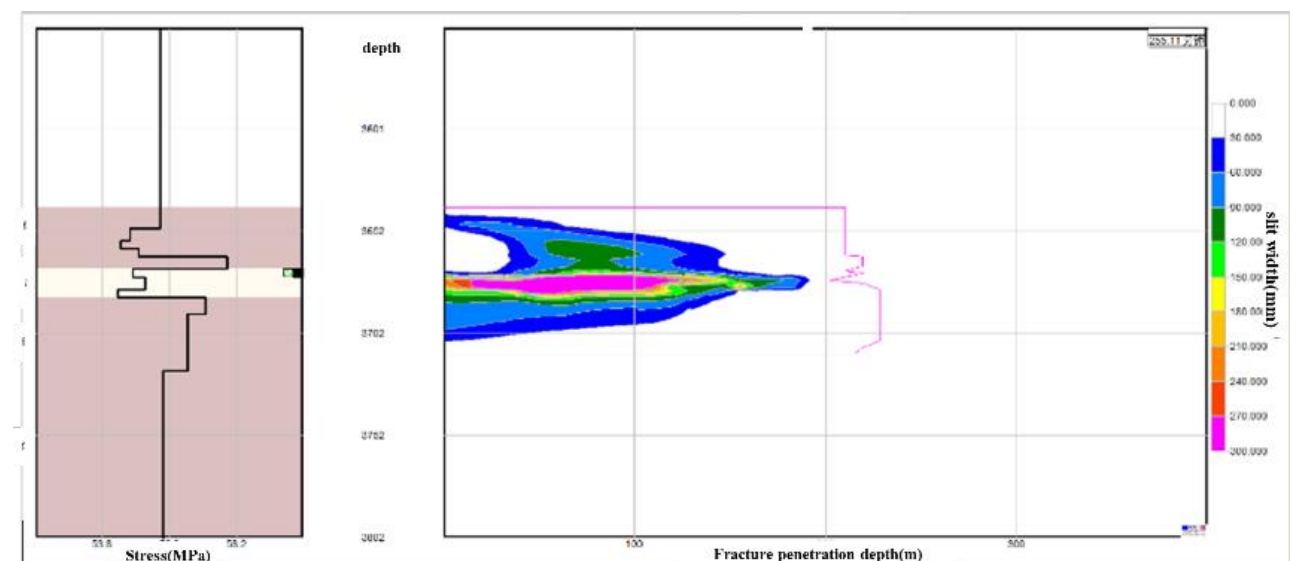


Fig. 13 Map of fracture support inflow capacity in well B

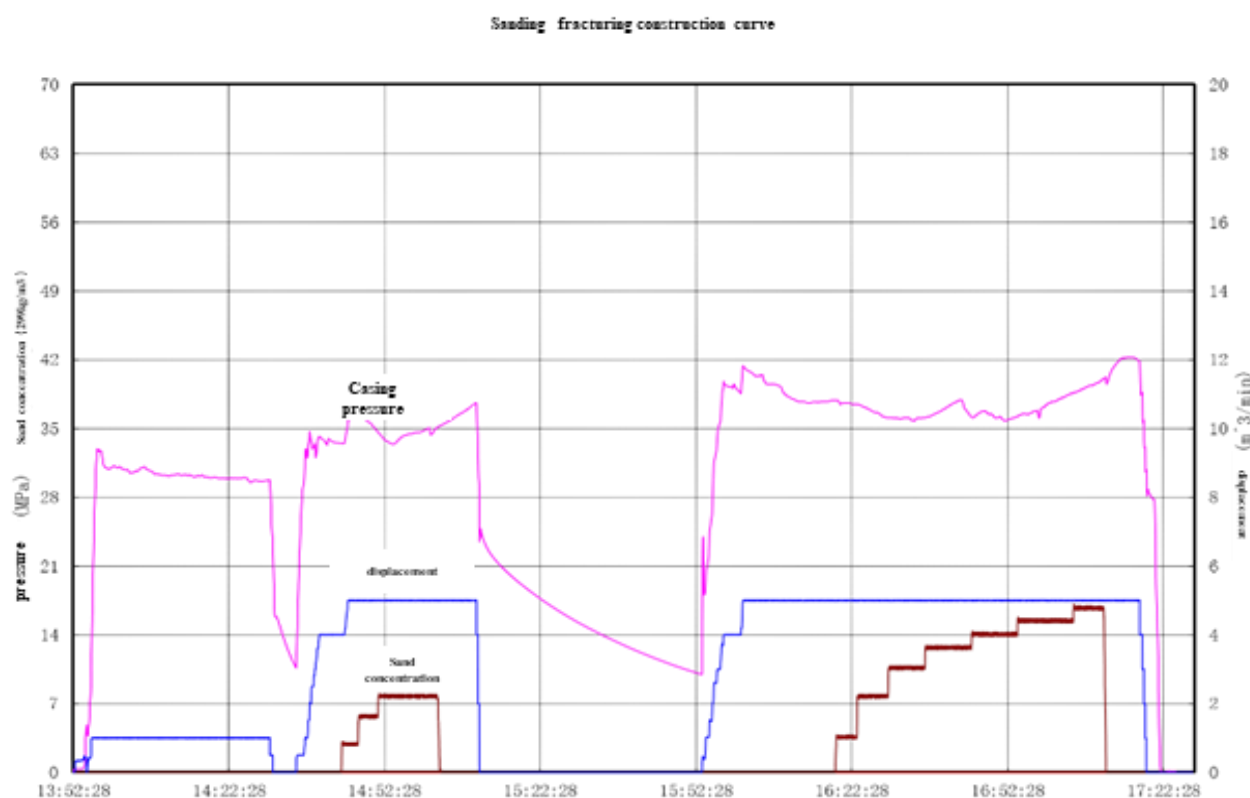


Fig. 14 B Well fracture support inflow capacity map

6. Summary

1. The water control fracturing process in tight sandstone gas reservoirs is significantly influenced by factors such as the stopping time of secondary sand addition, perforation location and construction parameters, among which the stopping time of secondary sand addition and perforation location have a significant impact on the water control effect.
2. For the two production wells in Su 59 block, the water control effect differs significantly. The water control fracturing program should be optimized for different reservoir characteristics, such as the horizontal principal stress of the reservoir compartment, rock mechanics parameters, reservoir physical properties and the location of the adjacent water layer.
3. After optimizing the progressive water control fracturing scheme for Well B, the construction parameters were 5 m³/min for the main pumping volume, 563.2 m³ of net fluid, 60 m³ of sand, 37.9% of front fluid, 50 min of stoppage time, 5.4×10⁴ m³/d of daily gas production after fracturing, 6.3 m³/d of daily water production and 131.08 m³/d of unobstructed flow.

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