Volume Fracturing Technology Application in the World's Largest Conglomerate Oil Field, Northwest of China

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Abstract: One billion-ton super large oil field of Mahu is the largest oil and gas exploration achievement in China in recent years and has become the most realistic replacement area for increasing reserves and production in China as the world's largest conglomerate oil field till now. According to the complex reservoir-forming conditions in Mahu Sag, poor reservoir property, strong heterogeneity, and large sand body span, hydraulic fracturing in this area was facing serious challenges in fracture initiation and proppant placement. It has deepened the concept of volume fracturing technology and improved the effect of reconstruction; advanced chemicals to optimize replacement and reduce costs; tackled key perforation bridge plug with production technology to improve the level of operation according to 5 year's stimulation experiences. The volume fracturing series technologies have been widely applied in 11 blocks and 97 wells in Mahu, including most of the exploration, evaluation, and development areas. For the tight conglomerate oil reservoir of Mahu, the fracturing and producing effects accompanied by economic development have been realized and effectively promoted, thus the average cumulative production increased by 37.5% per year.

Key Words: Tight conglomerate, Sweet spots, Volume fracturing, Mahu Sag, Engineering application.

1. INTRODUCTION

The Mahu mega oilfield, which was ascertained in late 2017, has a proven oil reserve exceeding one billion tonnes. now produces nearly 6,000 tonnes of crude oil per day, and is expected to achieve an annual production of 2.18 million tonnes of crude oil in 2020.

As of the end of May, a total of 79 crude oil wells in the oilfield had been put into operation, with an aggregate output of 4.85 million tonnes, according to Reservoir Evaluation Department of Xinjiang Branch of PetroChina. As per the plan, Mahu Oilfield will have an average annual new production capacity of 1.65 million tonnes from 2019 to 2020, and an average annual new production capacity of 1.1 million tonnes from 2026 to 2030. The annual output of Mahu Oilfield will reach 5 million tonnes in 2025 and continue stable production for 6 years [2,4,42].

Mahu sag is a conglomerate complex reservoir deposited in the Junggar Basin of Xinjiang, Northwest of China as shown in Figure **1**.

2. CHALLENGES

Conglomerate reservoirs are highly heterogeneous, thus it is difficult to evaluate "sweet spots". Based on geology data, it is so complex sedimentary genesis although there are high-quality reservoirs in Mahu tight conglomerate. It is a fine conglomerate body in the fan channel, which is discontinuously distributed in the conglomerate body in the sheet flow as it has thin oil layers (2-8m), interlayered distribution, and rapid lateral changes [4]. Generally, it contains strong heterogeneity in physical properties and rock mechanics parameters. Furthermore, there are many challenges due to the lithology characterized by a conglomerate and coarse sandstones interbedded with medium and fine sandstones that are normal form graded bedding sequences. Therefore, the rock texture differs significantly and can range from massive conglomerates to laminated pebbly sandstones. In addition, the oil-bearing grade also varies over short intervals, even in 1 meter when the depth of the pay zone varies from 2600 to 3300m.

The drillability of conglomerate in the Mahu region of Junggar Basin is poor because of its strong heterogeneity and high grinding. Moreover, the severe heterogeneity of conglomerate is characterized by low permeability (generally lower than 0.1md), micron and nanoscale pore throat, and nonlinear seepage; therefore, multistage volume fracturing becomes the vital technique for production.

3. MULTISTAGE VOLUME FRACTURING TECHNIQUES

Reservoir awareness and process reliability are key factors that affect the effectiveness of fracturing

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Figure 1: Location map of Junggar, Northwest of China.

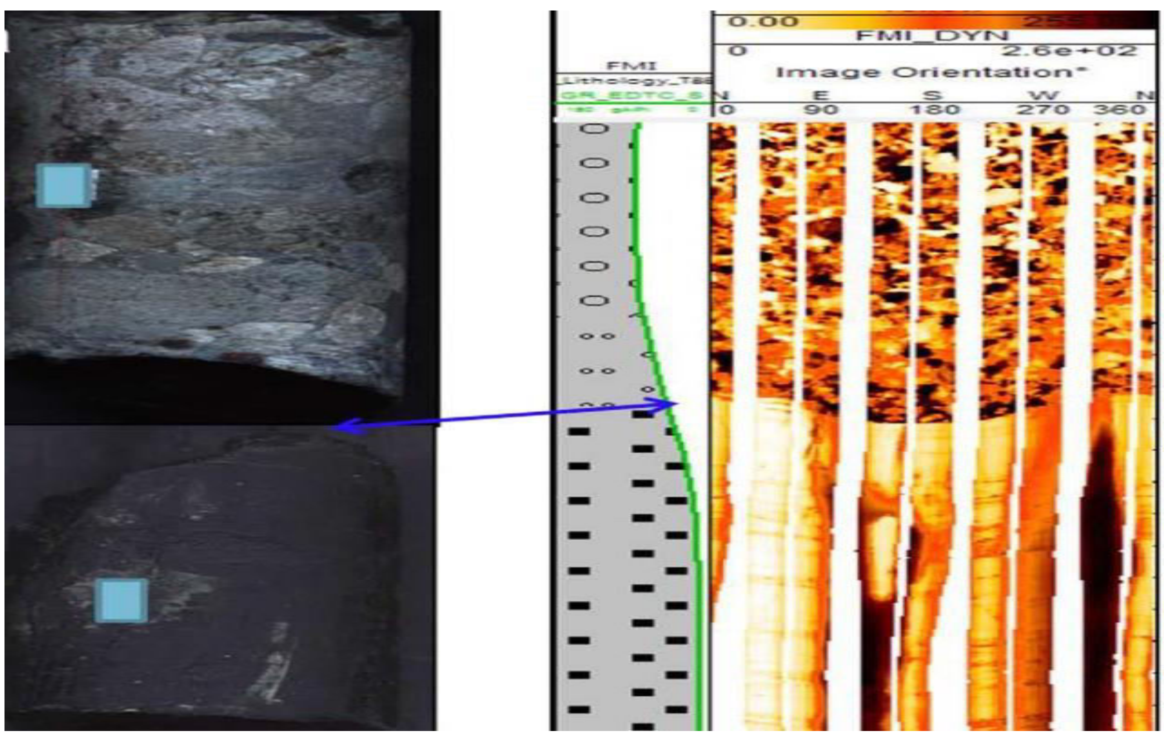

Figure 2: High heterogeneity of rock texture and oil-bearing grade.

reformation and construction efficiency. Adhering to the "problem-oriented" approach along with focusing on technical shortcomings and reservoir characteristics, the following four technologies are developed for Mahu Sag.

3.1. Elaborate "Sweet Spots" to Improve Volume Fracture Efficiency

In the Baikouquan Formation, the fractures are not developed, the stress difference is large, the rock is

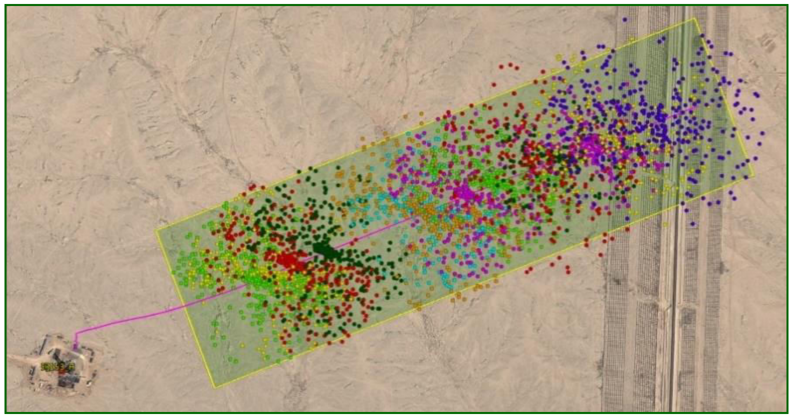

Figure 3: Micro-seismic interpretation results of well Ma-15X.

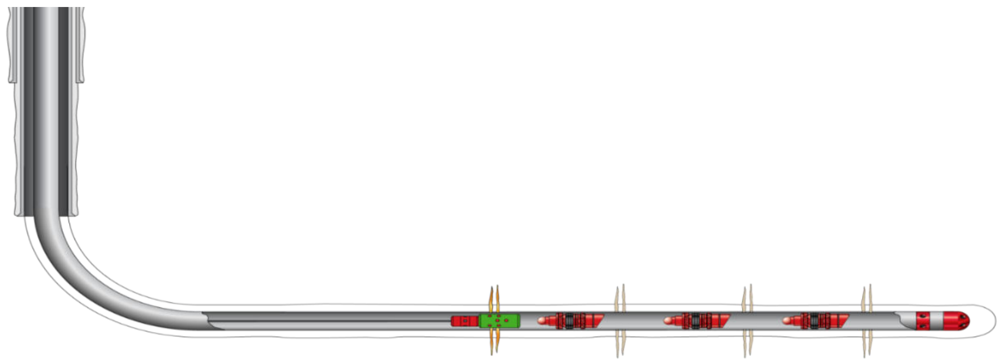

Figure 4: Subdivision cutting volume fracturing process.

very tight, and the artificial fractures are mainly single-sided. Increasing fracture distribution density to subdivide the reservoir, and increasing the contact area between the fracture and the reservoir to cut it are the main ideas for volume fracturing [1]. The fracturing process for subdivision cutting accompanied with perforated bridge plugs has been formed, and the bottom seal dragging of coiled tubing and the infinite cementing sliding sleeve fracturing process have been tested, until the average stage spacing is dropped from 40m to 30m, with a minimum of 15m in 2019.

Following the integration of geology and engineering, multi-parameter comparative analysis of "geological sweet spots" and "engineering sweet spots" are mentioned below.

The existing conglomerate category principles are not standardized. For instance, sandstone and mudstone are used as the main category principle which cannot distinguish conglomerate reservoirs, such as "glutenite" and "unequal-grained conglomerate", etc., while the category of the conglomerate grain size is not uniform [3-7]. Therefore, the new standard divides the particle size into 2～8mm as Fine gravel, and the particle size of 8～64mm is further divided into Small gravels of 8-16mm and Medium gravels of 16-32mm in diameter, and other compared with the same type of particle size classification standard. Thus, the standard particle size classification is finer and more scientific which can be seen in Ma-131 well block.

According to the newly formulated conglomerate lithology category standard after refinement, take Ma-131 well block as an example, its lithology can be divided into medium conglomerate and small conglomerate from north to south. Some of those are transitted to fine conglomerate as the above figure.

Secondly, determining oil saturation is the core of the division of geological "sweets" parameter. When determining the geological “sweet spot” in the study area, the oil saturation, So, is highly dependent on the porosity and other important reservoir parameters such as permeability and oil saturation, and oil-bearing saturation that characterize the productivity of the oil layer [8-11]. The relationship between the degree of So and the intensity of oil production divides the “sweets” into 3 categories:

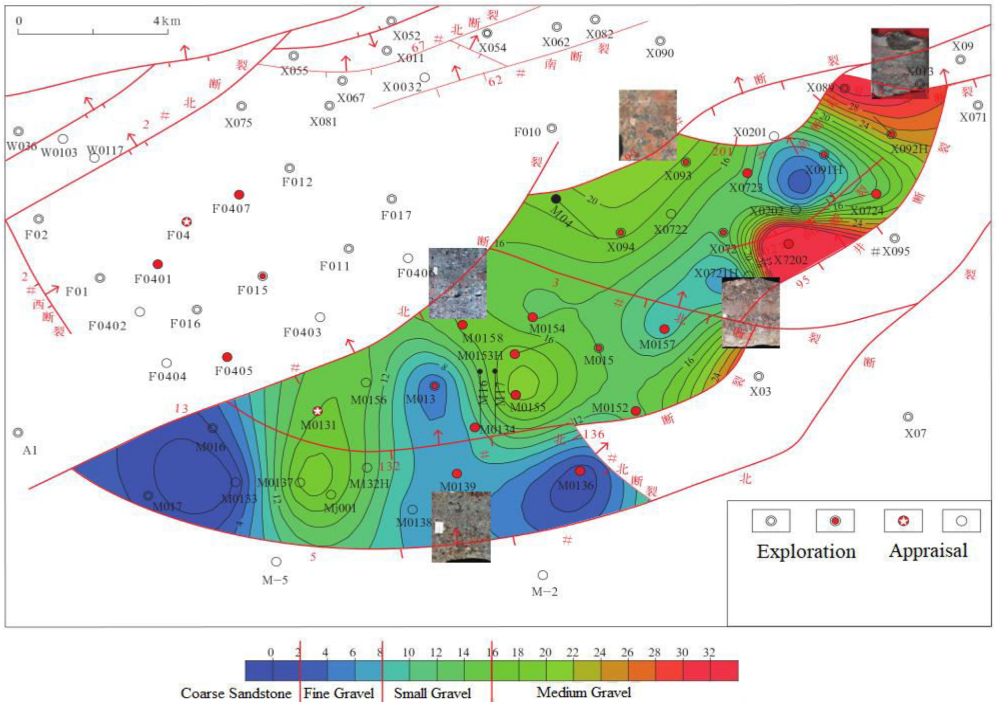

Figure 5: Contour map of grain size distribution for the Baikouquan Formation in Triassic of Ma-131well block.

Class I; So is greater than 60%;

Class II; So is 50%～60%;

Class III; So is 45%～50%. The production capacity of Class I "Sweets" is 5 times that of Class III even under the same process conditions accompanied with the same pay zone thickness.

Thirdly, classification of "sweets" combining geology and engineering. The main evaluation parameters of geological "sweets" are porosity φ and oil saturation So. In contrast, the evaluation of engineering “sweet spot” is the parameter of Young's modulus E [12-20].

This classification method can be further applied to Mahu sag for the evaluation and analysis of each block in the area, and guide the development practice of the entire reservoir.

Moreover, according to optimization of perforated well sections and optimization of fracturing scale, the below volumetric fracturing techniques have been implemented to improve the layer transformation effect.

1) High pre-fluid ratio: 60~70%, slippery water ratio 35~60%.
2) High sand ratio and more sand: average sand ratio 20-25%.
3) Large sand volume transformation: single-stage sand volume is more than 75m^3, single well is up to 1900m^3.
4) Large liquid volume into the well: a single stage of liquid volume above 1000m^3, a single well with a maximum of 34913m^3.
5) Large displacement construction: slippery water 8~10m^3/min, guar gum 6~8m^3/min.

There is no bottom water in the Baikouquan Formation reservoir of Mahu, which is suitable for large-scale volume transformation. The average liquid

Table 1: Classification Standard of P3 Oil Layer in Upper Permian in Mahu-1 Well Block

Category	Geological "Sweet"	Engineering "Sweet"	Average Test Production Rate, Ton/d
Class I	φSo≥ 0.035	E ≥ 35000MPa	15.18
Class II	φSo< 0.035	E ≥ 35000MPa	13.43
Class III	φSo≥ 0.035	E <35000MPa	6.79
Class IV	φSo< 0.035	E <35000MPa	5.09

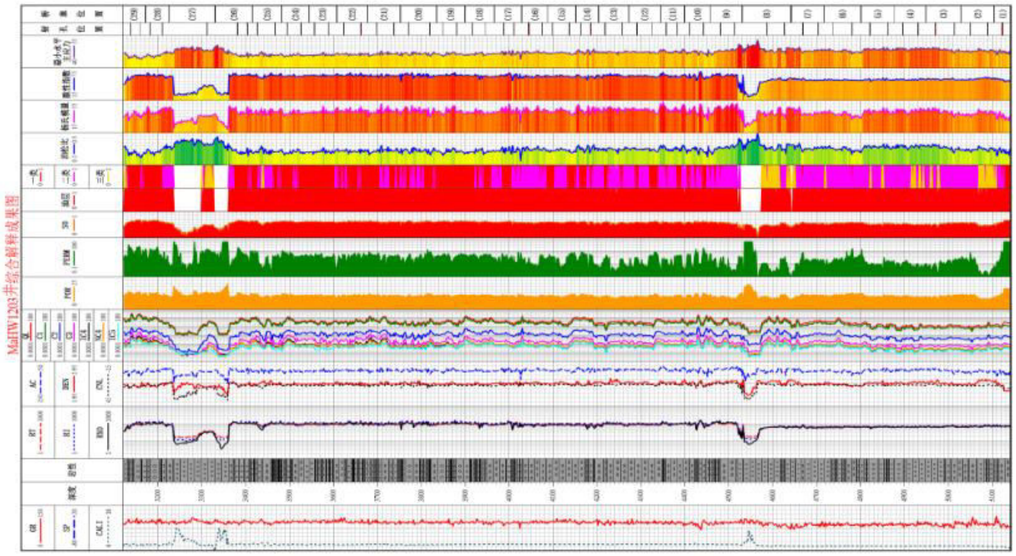

Figure 6: Engineering and geological parameters.

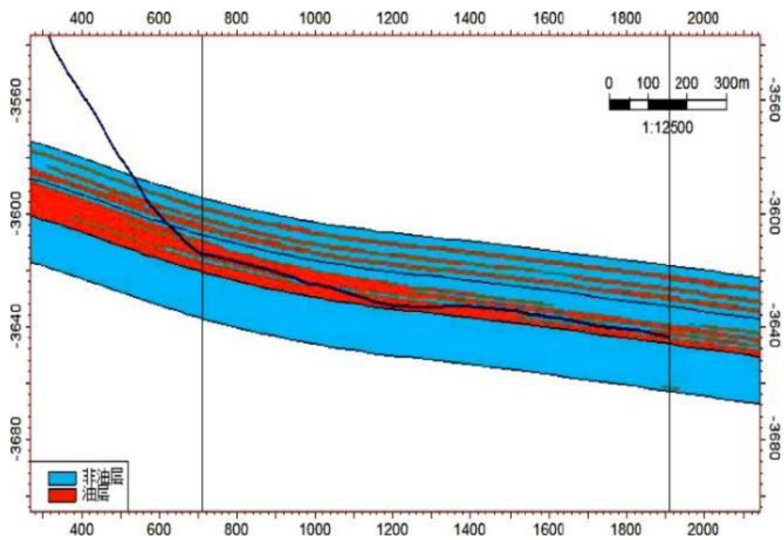

Figure 7: Schematic diagram of horizontal well trajectory.

volume per stage was 1245m^3 in 2019, which is an increase of 7% compared with 2018 accordingly.

In response to problems such as few proppant embedding in the reservoir and low conductivity, the sand ratio has been increased to increase the concentration of sand paving. The average sand volume per stage was 76.9m^3 in 2019, which is an increase of 9% compared with 2018.

3.2. Apply Fit-for-Purpose Chemicals to Reduce Costs

A multifunctional additive has been developed that has the effects of anti-swelling, drainage, demulsification, sterilization, etc., which simplifies the continuous mixing process and forms a "standardized" formula of "slip water + low concentration guar gum" composite fracturing fluid for horizontal wells in Mahu. That block optimization is based on an oil sample and water quality analysis, and through experimental adjustments, a "personalized" ratio is formed. The amount of thickener is reduced by 20%, and the core damage rate is reduced by 47%.

Proppant, fracturing fluid materials, and dosage substitution chemicals have been tested to reduce material costs:

- Medium-density ceramsite has been replaced by low-density ceramsite, and ceramsite has been replaced by quartz sand;

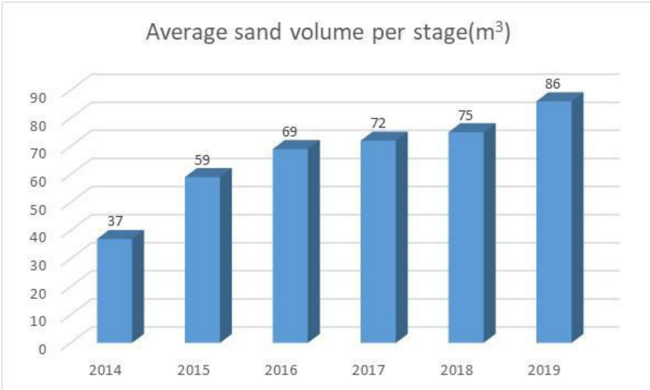

Figure 8: Variation trend diagram of average sand volume in the horizontal wells of Mahu.

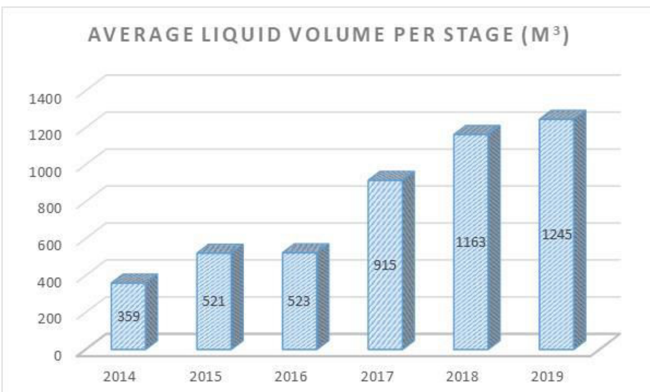

Figure 9: Variation trend chart of average liquid volume in the horizontal wells of Mahu.

- The hydration efficiency of the compounding vehicle has been improved to make the conventional guar gum to be sticky and replace the instant guar gum;
- The fracturing displacement rate has been improved and proppant density has been reduced to make guar gum concentration by 20%;
- The percentage of slippery water has been increased to 60% for replacing guar gum pre-fluid;
- Clean water has been replaced by fracturing flow-back fluid and boiler purified water for liquid preparation;
- The gel-carrying sand has been replaced by slippery water pulse sanding to add sanding in the whole fracture process.

3.3. Tackle Key Perforation Bridge Plug to Improve Operation Success Rate

The horizontal well of Mahu is mainly composed of three casing strings structure, which is completed by a 5-inch casing in the end. The type-73 perforating gun is used in the early stage. The perforation is imperfect and the fracturing operation is difficult. For this reason, the type-86 cluster perforation is specially researched and applied. Furthermore, the flexible short section with rollers has been developed to reduce the rigidity and

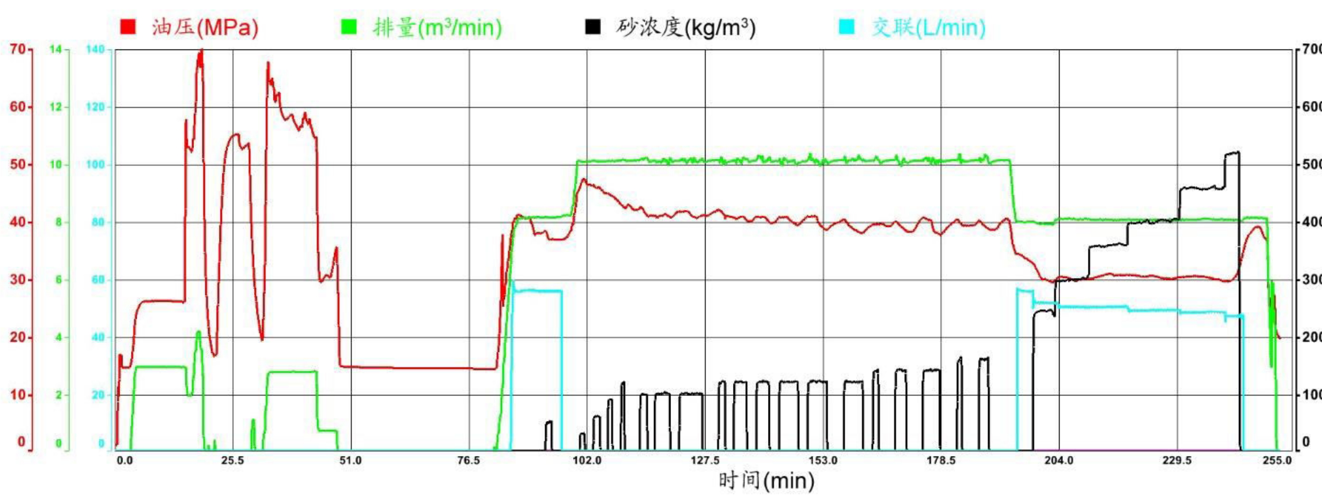

Figure 10: Test curve of pulse sanding with slippery water in Ma-X42 well.

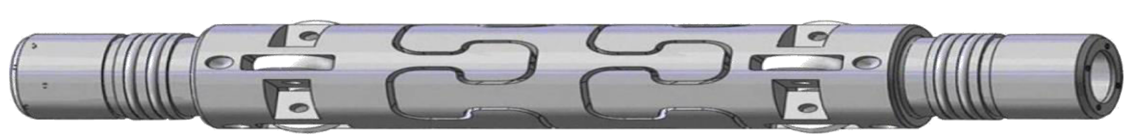

Figure 11: Flexible short section with roller.

friction of the tool string, improve the construction safety and success rate.

For the 5-inch casing, the high-hardness slips are screened through the mounting test, and non-standard bridge plugs are customized to ensure reliable engagement between the bridge plug and the casing. In accordance with API standards, a suitable domestic high-steel casing has been developed, where the quick-drilling bridge plug has a relatively small outer diameter, strong sealing, and suspension capabilities. Thus, making it easier to pump.

Standardized operation processes have been formulated and the success rate of operations has been significantly improved according to the optimization of equipment and process technology [21,22]. The horizontal well-perforated bridge plugs have been used for 18 well times, with 339 bridge plugs and 685 perforated clusters in the Mahu sag.

The one-time success rate was 95.5%, and the single-level duration was 4~6h according to 255 stages statistics in 2018. Meanwhile, it was improved to 549 stages in 2019, so the one-time success rate had been 99.3%, and the single-stage time limit was reduced to 3~4.5h. Three new records have been developed, which are maximum operating well depth: 5932m, maximum pumping pressure: 62.5MPa; the shortest cluster spacing: 5m.

3.4. Design New Well Flush Tools to Ensure Operation Safety

A combination of pre-flushing and well flushing tools has been designed. The first pass is used to clean the sediments in the wellbore, and the rotating scraping function is added based on the design ideas of the cuttings bed removal too. Moreover, the second pass is used to clean the well wall adhesions and the rotating jet flushing head has been developed. Thus, the spiral scraping through-well gauge has a dual role to improve the cleanliness of the well wall.

The new well-flushing tool string was put into field application at the beginning of 2019, and the complicated problem of the first few levels of perforation bridge plug combination has been solved.

Regarding the structure for a pilot test to pass through the well flushing tool string, the completion of horizontal section is ‘sliding sleeves + open hole packers, and the inner diameter of tube is 4.5 inches. The fracturing efficiency is increased by 50% by the modified well flushing tool string.

According to the analysis of the structure, material, and debris migration law of the bridge plug in the well, combined with wellhead pressure and gas-oil ratio, the high-pressure plug-in well control conditions and tool string combination are clarified to form a safe,

Table 2: API Test Results for Self-Developed Speed-Drilling Bridge Plug of D1-V3

No.	Device Under Test	Temperature, °C	Liquid	Isolation Pressure, MPa	Hanger Capacity	Releasing Pressure, MPa
1	JT-105	150	Water	90	NO	16.9
2	JT-105	150	Water	105	NO	19.89

The first well flushing tool string structure is shown below.

Figure 12: Slips/rivet connector + heavy-duty motorhead assembly + hydraulic oscillator + screw drilling tool + chipping pear mill.

The second well flushing tool string structure as below.

Figure 13: Slips/rivet connector + heavy-duty motorhead assembly + spiral scraping through well gauge + rotating jet flushing head.

applicable bridge plug drilling and grinding process plan and supporting technology [23].

Main Specifications:

- The number of drilling and grinding in a single trip: 15, maximum depth is 4866.73m in well Ma-X1
- Single well drilling and grinding number: 28, maximum depth is 5142.04m in Ma-X2
- Maximum drilling pressure: oil pressure 62.7MPa, casing pressure 34.5MPa in well Ma-X6
- Maximum drilling depth: 5485m@27MPa in well Ma-X7
- Single-trip drilling and milling sliding sleeve number: 15 pieces, maximum depth is 4000.23m in well Ma-X9

4. WAY FORWARD FOR VOLUME FRACTURING IN MAHU

4.1. Take Haynesville as Benchmark

The Mahu tight glutenite reservoir is similar to Haynesville shale gas in terms of reservoir depth, construction pressure, and rock mechanical properties. The Haynesville development model is a good example to be learned [24]. As recorded in the paper, Haynesville has an average buried depth of 3598m, 3140m in the northwest, and 4268m in the southeast. Furthermore, the rock in the target layer is soft, the content of clay is high (35~43%), and the problem of proppant embedding is prominent [26,27]. The construction pressure usually exceeds 70MPa, which requires 2 times of the fracturing water horsepower of other shale reservoirs.

4.2. Broaden the Understanding of Subdivision Cutting Volume Fracturing

According to the analysis for the influence of geology, oil reservoir, and engineering factors on the development effect of horizontal wells and the exploration of the internal relationship of fracturing intensity, construction scale, cumulative production, decline rate under different porosity and permeability conditions, the "subdivision cutting" fracturing process parameters have been further optimized and economical design parameters have been improved [25-35].

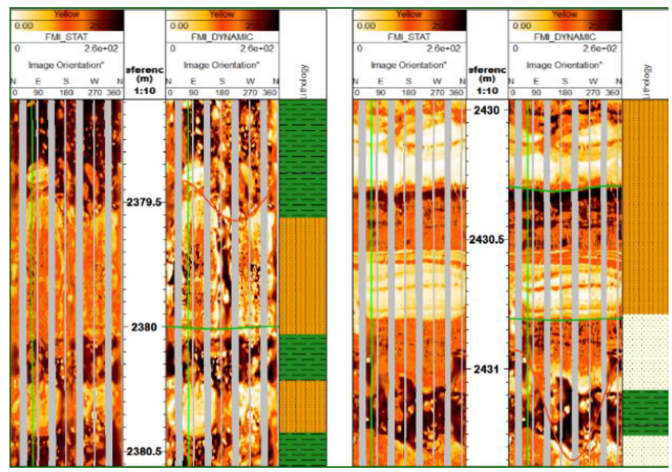

Figure 15: FMI in well Ma-4X of Mahu sag.

4.3. Deepen the Research of Oilfield Wastewater Mix Technology to Reduce the Pressure on Environmental Protection

The fracturing flow-back fluid is mainly adopted for reinjection treatment, with a small recovery scale and

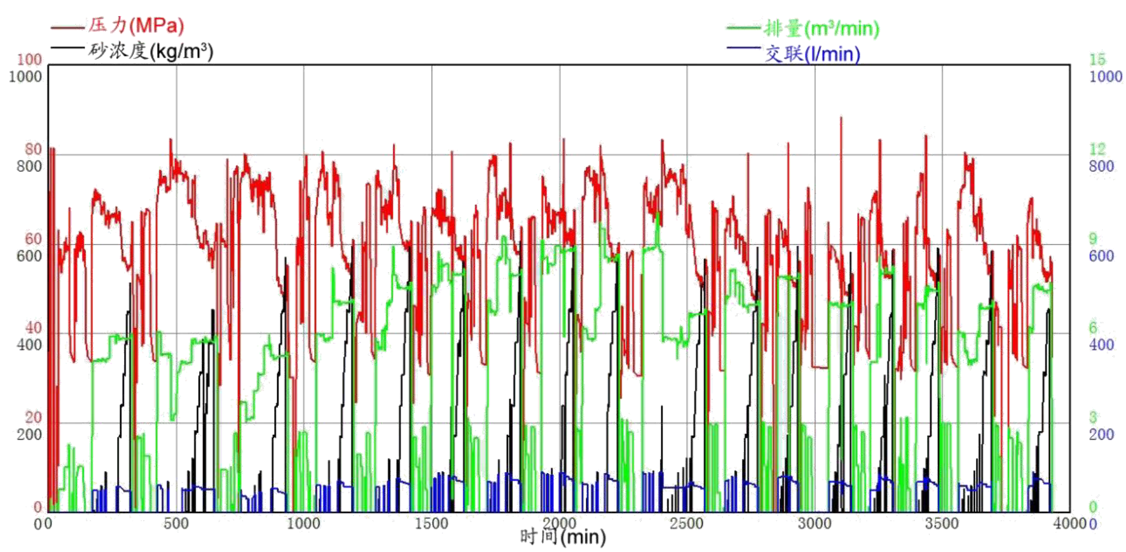

Figure 14: Horizontal well-staged fracturing construction curve in Mahu.

low utilization rate in Mahu sag [36,37]. Then the fracturing flow-back fluid in the Ma-X18 well area can be used for fracturing fluid distribution in new wells. Moreover, the fluid distribution process has been optimized in the Ma-X4 well area, and the scale of high temperature purified water for heavy oil thermal recovery has been expanded.

4.4. Enrich Fracturing Technology Means to Improve Transformation Efficiency

The perforation bridge plug joint production process has been improved further. The released horse-head, visual tension system, self-developed fast-drilling bridge plugs, and soluble bridge plugs have been developed to reduce tool costs and improve coiled tubing bottom seal drag fracturing [38-41]. Furthermore, the reliability of cementing sliding sleeve fracturing tools has been further improved to shorten the transition time between stages.

5. CONCLUSIOINS AND RECOMMENDATIONS

In response to the transformation challenges of Mahu tight conglomerate reservoirs, based on the concept of "fracture-controlled reserves", the authors have innovatively proposed and applied horizontal well subdivision cutting volume fracturing, large-displacement reverse mixing and high-efficiency fracture creation, and large-scale energy storage. A series of technologies such as engineering and geology “sweet spots” combination and energy fracturing has maximized the effective volume of tight conglomerate reservoirs and the production effect of horizontal wells [42].

Since 2014, the integrated horizontal well volumetric fracturing technology for tight conglomerate reservoirs has been applied to 97 well times in the Mahu area. The use of cementing bridge plug cluster perforation partial pressure technology meets the requirements for the transformation of cementing horizontal wells with 5in casings within 6000m in depth and 2000m in horizontal section. The maximum well depth reaches 6008m and the maximum horizontal section length reaches 2022m. The interval between fractures is reduced from 70m to about 30m in the early stage, and the degree of reservoir reconstruction is more adequate; the proportion of slippery water is increased to more than 70%, and a large amount of liquid is

Figure 16: Flow liquid recovery processing device.

Figure 17: Volume fracturing at Mahu field.

injected into the formation to maintain the formation energy. The drilling penetration rate of the oil layer reached up to more than 90%, and the average cluster spacing in the Ma-131 well block decreased from 67 m to 35 m. In sum, the average cumulative production increased by 37.5% per year.

Furthermore, it is suggested to strengthen theoretical research on conglomerate fracture propagation mechanism, nonlinear seepage and imbibition, continuously optimize fracturing materials and fracturing scale, and further improve oil reservoir recovery. Finally, due to different ground-surface conditions between China and the US, the feasibility of increasing pad well numbers should be studied under mountainous conditions in China.

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