Application of Downhole Micro-seismic Technique in Shale Gas Fracturing Optimization of Fuling, China

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Abstract: The downhole micro-seismic method has successfully applied to well fractory fracturing development in Jiaoshiba block, Fuling shale gas reservoir in September 2015. The new concept and understanding have accumulated. Combing the actual construction condition of micro-seismic monitoring in JY AA-BB well groups, we reviewed briefly the downhole micro-seismic monitoring technology and then summarized multi-disciplinary experience and understanding. The staged fracturing process level improved and productivity increased with the further development of shale gas field. Results show that the understanding of micro-seismic method has played a guiding role in the optimization of fracturing process and site construction adjustment of other wells in the same area, which increased the productivity and created a huge economic benefits with a broad market prospects.

Keywords: Fuling shale, downhole micro-seismic monitoring, multi-stages fracturing, shale gas development.

1. INTRODUCTION

Fuling shale field located in Jiaoshiba faulted anticline region, where the main block structure is gentle and the edge retained by West Da'ershan, Shimen, Diaoshuiyan and Tiantaichang faults. Generally, it is characterized as wide in the south and narrow in the north, steep in the north-south and gentle in the middle. The main body structure lies in low curvature with no fractures, while it has high curvature in the east and west wings with natural fractures developed relatively. The JY AA-BB well groups is located in the southwest of the principal part of the faulted anticline, which is influenced mainly by Diaoshuiyan fault. Few clusters of BB group, which is situated in the north, located in the fractures-developed area, while others in relatively gentle region with no fractures developed (Figure **1**).

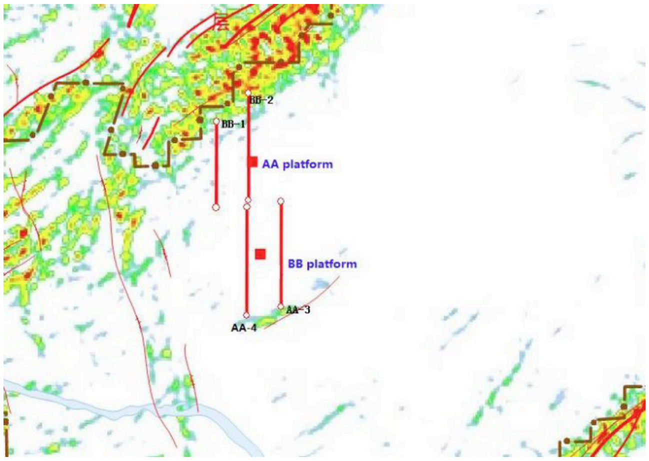

Figure 1: Curvature attributes of TO3w reflecting layer in JY AA-BB well groups.

It's the first successful application of downhole micro-seismic real-time monitoring on JY AA-BB well groups staged fracturing in Fuling shale reservoir. Compare with the ground surface micro-seismic monitoring is very difficult to laying the wires in the mountainous region, and the signal will be interference by the native folks and traffic system. Thus, we choose downhole micro-seismic monitoring equipment. The monitoring used 12 downhole three-component geophones with the ability of high temperature, pressure and corrosion resistance.

The monitoring process mainly includes the following parts:

Firstly, based on acoustic logging curves of fracturing wells (4 wells in JY AA and BB platform) and monitoring wells (JY AA-5HF), we establish 2D layered velocity model combining with VSP and surface seismic data.

Secondly, according to the signal of detonating cord, we determine the location of three-component geophone.

Thirdly, we adjust the velocity model based on the signal of P wave in order to locate the breakdown event in the excitation point.

Fourthly, based on the fact that the large energy events typically located near the perforation points, we diagnose the micro-seismic event and threshold of micro-seismic events to pick up the initial P wave and S wave quickly and accurately.

Finally, we determine the location of micro-seismic events by the Tian'an ray-tracing method and Geiger location method. When the geophones receive the

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energy signal and transmit to surface equipment, via professional soft processed automatically and artificial screening to pick up effective break events, then located the events location, energy level and magnitude by inversion calculation, so that fracture network information can be judged real-time preliminary including spatial distribution, azimuth direction and so on.

This downhole micro-seismic monitoring has completed in 4 wells, 104 stages fracturing and conducted real –time artificial fracture extension evaluation. Results show that effective micro-seismic events are 15059, fracture length ranged from 100 to 656m, and stimulated reservoir volume (SRV) is $8730.4\times10^{4}m^{3}$.

2. COMPREHENSIVE COMPARISON OF FRACTURING MICRO-SEISMIC

JY AA platform completed 56 stages monitoring in total. Because the distance from the horizontal toe to micro-seismic geophone is pretty long (2345 and 2413 m), a few effective events, about 5 to 14, can be detected in the first 6 stages, which can not be accurately described the fracturing trend and geometry size. With the monitoring distance getting closer to 2000 meters or less, the number of micro-seismic events obviously increased in the subsequent stages. The length of the monitoring fractures ranges from 229 to 642 meters. JY AA platform completed 48 stages monitoring in total. The first 4 stages are influenced by the monitoring distance. The events number increases obviously in the subsequent stages: less than 2000 meters. The length of the fracture length ranges between 199 to 656 meters (Figures **2** and **3**).

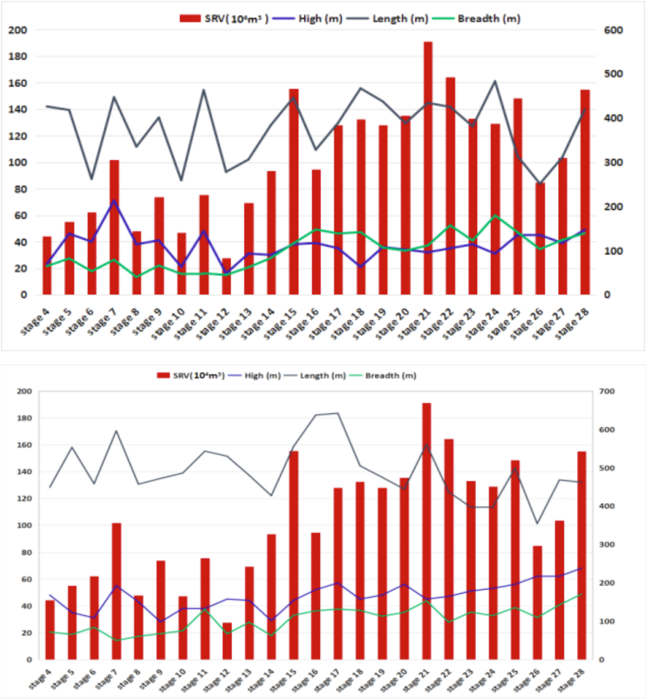

Figure 2: Comparison of monitoring physical dimension and SRV of JY AA-3HF, AA-4HF.

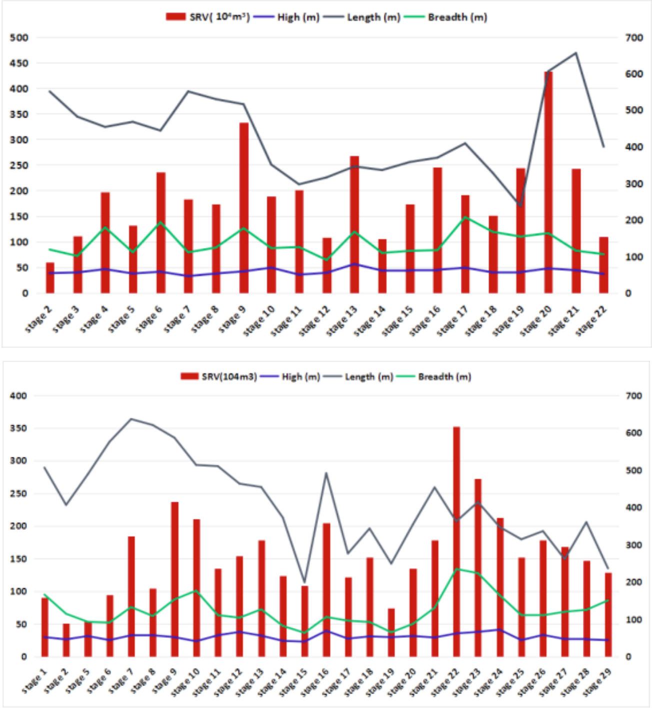

Figure 3: Comparison of monitoring physical dimension and SRV of JY BB-1HF, BB-2HF.

2.1. Transformation between Adjacent Stages

From the vertical view of micro-seismic events distribution in JY AA-BB well group platform, we discover that:

(1) fracture length is shorter than the expected which indicates that the fracturing design and site construction have some flaws.

(2) some adjacent stages overlap together seriously, which may lead to the waster of investment cost, and indicate that it is more or less unreasonable of the fracturing perforating design. (The red ellipses show the stages overlap region in Figure **4**).

Through the statistics of the micro-seismic events between two adjacent fracturing stage, we found that lots of stages overlap together in JY AA-BB platform. The width of the overlap area between 30 to 139 meters, mostly about 50 meters, Figure **5**.

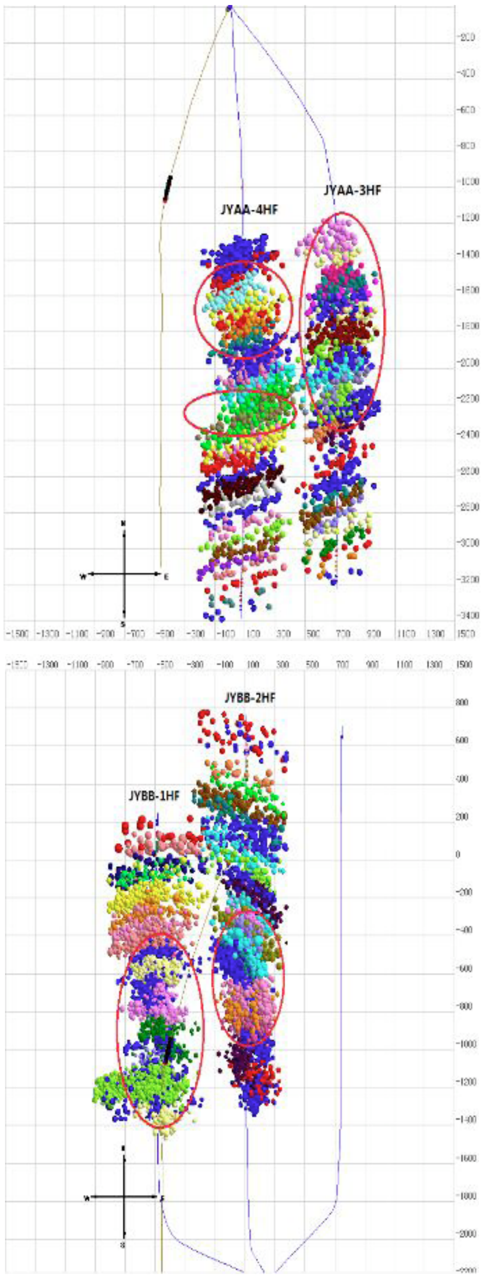

Figure 4: Vertical view of JY AA and BB platform monitoring results.

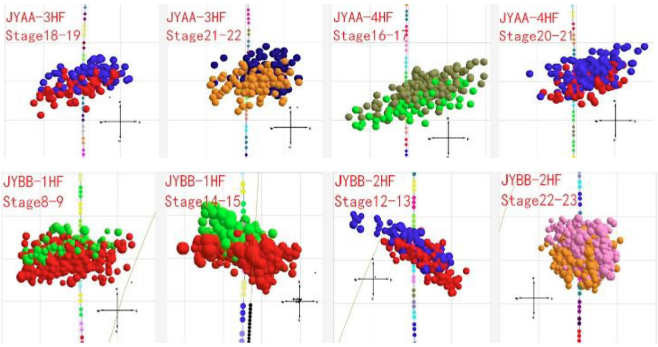

Figure 5: Diagram of overlapping stages of micro-seismic events.

2.2. Direction of Fracturing Network Distribution

By projecting micro-seismic events into seismic attribute such as curvature, coherence and so on, we found that micro-seismic events with magnitudes greater than -2.5 were distribute along the horizontal maximum principal stress, Figure **6**. We also found that JY AA-3HF and JY AA-4HF artificial fracture network in the same direction of the horizontal maximum principal stress, however, JY BB-1HF and JY BB-2HF changed, which is not consistent with the principal stress direction, Figure **7**.

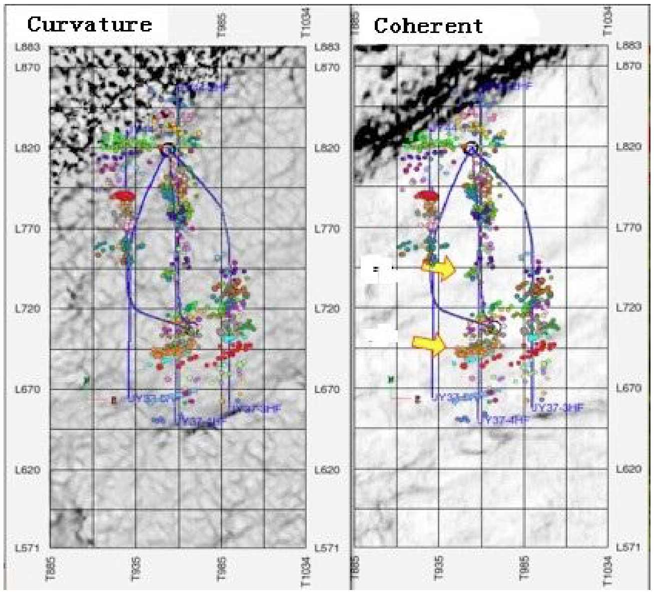

Figure 6: Projecting micro-seismic events into seismic coherence attribute.

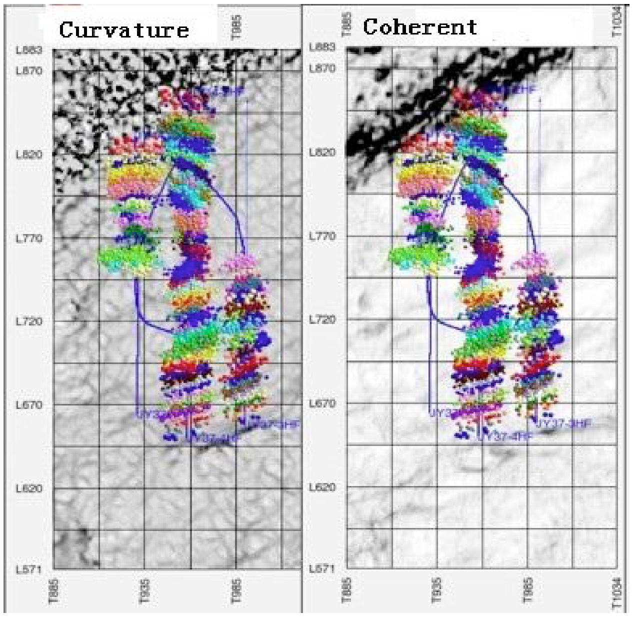

Figure 7: Projecting micro-seismic events into seismic coherence attribute.

The reason of the horizontal distribution of artificial fractures in JY BB-1HF and JY BB-2HF changed mainly due to the influence of the local stress. In the early stage of zipper type fracturing, the direction of artificial fracture network of JY BB-1HF was in accordance with the the horizontal maximum principle stress. When the JY BB-2HF fracturing, the local stress of the formation changed resulting in deflection of the fracture distribution at the toe of the JY BB-2HF.

However, the direction of the strong micro-seismic events that larger than -2.5 magnitude did not change with the the direction of the maximum principle stress, which shows that maximum principle stress has not changed. The overall distribution changed only after artificial fracture in the further extension of the process. With the fracturing progress adjustment, when the rate of progress surpass than JY BB-1HF, the network direction of JY BB-2HF is consistent with the direction of maximum principal stress. To some extent, while the JY BB-1HF was affected by local stress and network distribution (see Figure **8**).

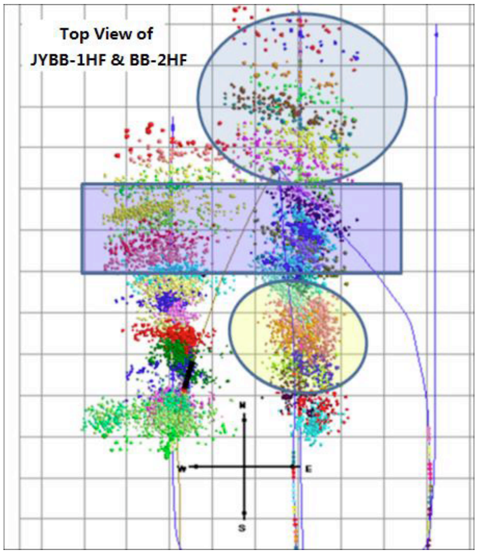

Figure 8: Micro-seismic distribution of JY BB platform.

2.3. Relationship with Main Reservoir Physical Parameters

It may show different reservoir physical properties in shale gas reservoir due to different section of well trajectory. GR is one of the most basic parameters of well logging. Base on the micro-seismic monitoring, we found that the GR value higher in the adjacent fractured stages, the less micro-seismic events monitored, the smaller of SRV (see Figure **9**). Generally, the higher GR value, the less easier to be fractured due to high mud content of the interval.

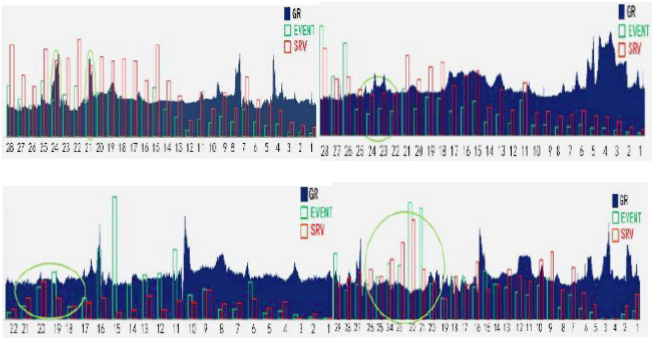

Figure 9: Comparison of micro-seismic events with GR logging and SRV.

Young's modulus is a physical quantity characterizing the tensile or compress stress within the limit of elasticity material. Within the limit, the stress is proportional to the strain, the ratio of which is called the Young's modulus and it depends only on the material itself. The Young's modulus indicates the rigidity of material. The greater Young's modulus, the less prone to deformation.

The micro-seismic monitoring of JY AA-BB well group shows that the area with greater Young's modulus, the more energy magnitude is relatively large and the fractures are likely to crack. There may be lithology variation in the place the Young's modulus mutation site changes. At that time, fracturing is prone to produce bedding fractures (see Figure **10**).

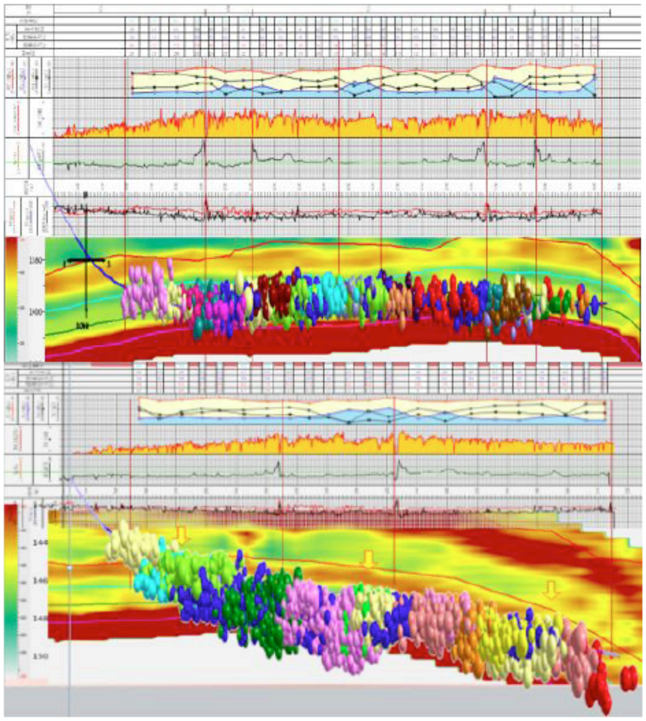

Figure 10: Relationship of micro-seismic events with the Young's modulus.

2.4. Style of Slurry Rate Establishment at Pretreatment

There are two style slurry rate establishment in the gas field, one is step up style, one is rapid up style. The rapid up style is push the hydraulic pressure on the formation in a very short time, which has a similar impact on water hammer effect that helps to reduce the breakdown pressure and makes the interval more broken. Even though higher slurry rate is one of the targets that shale gas fracturing pursuit, it should be combined with reservoir geological conditions which determine the speed of slurry rate establishment [10-11].

Statistical analysis of JY BB-1HF micro-seismic events of the horizontal well through the same layer, we can found that rapid up style has more number of events than step up style in ① and ③ layer, and the same as swept volume. But the ratio of ③ layer is smaller than in the ① layer, which means the rapid up style is more conducive than ① layer. Compared with ④ layer, the opposite pattern indicates that step up style is more conducive in ④ layer, Figure **11**.

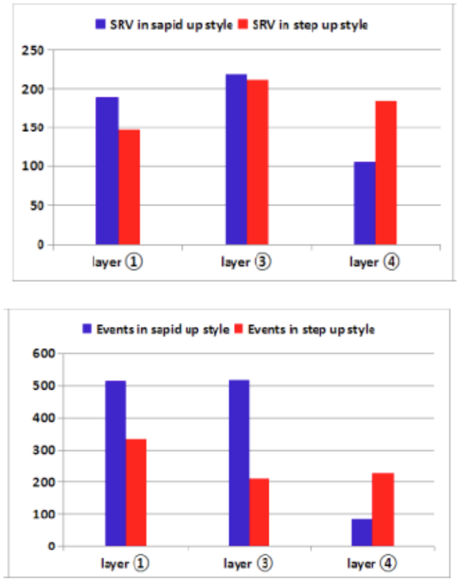

Figure 11: Comparison micro-seismic character with different slurry rate style in different layers of JY BB-1HF.

The same statistical analysis method of JY BB-2HF, we found that rapid up style has more swept volume but less number of events. The ③ layer has the opposite pattern, which means the rapid up style is more conducive in ① layer and step up style in ③ layer. The rapid up style is more conducive in ② layer that has more swept volume and micro-seismic events, Figure **12**.

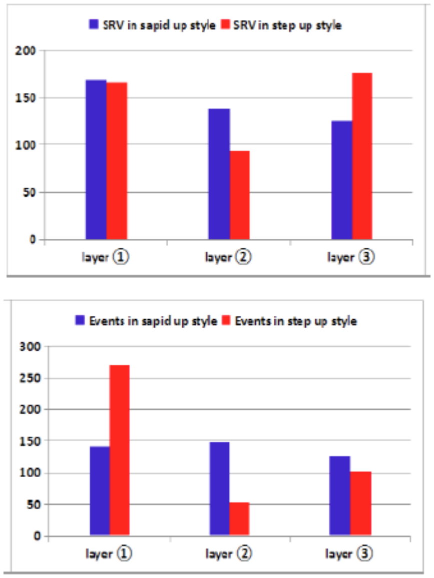

Figure 12: Comparison micro-seismic character with different slurry rate style in different layers of JY BB-2HF.

Generally speaking, if the pressure window sufficient, it's more conducive in ① and ② layer with the rapid up style in pretreatment stage, and step up style in ③ and ④ layer. Aiming at the main layer, the slurry rate and breakdown pressure are greater, and the SRV are relatively greater. The SRV may be affected by the breakdown pressure and slurry rate comprehensively.

2.5. Fracturing Scale

The effective development mode of shale gas is called Large Fluid Mount and High Slurry Rate. According to the current equipment capacity and development of Fuling shale gas reservoir, it is considered that the rate between 12 to 14 m^3 per minute can meet the requirement of reservoir stimulation. However, the optimization of the amount of fluid has been still in the exploration.

The result of micro-seismic monitoring in JY AA-BB well groups shows that the SRV increases with the increase of fluid volume in different stages. The fracture pattern maintains when the volume reached 1200 to 1600 m^3 and it is not obvious for fracture propagation if continuous water injection occurs (see Figure **13**).

The profile of the fracture network has been formed basically when the fluid volume reached $1600m^3$ according to the micro-seismic events condition of the 4 wells. The increase of micro-seismic events is not too much when the fluid injection volume more than

2000m^3. The growth rate of micro-seismic events is continuous weakening when about 900 to 1900m^3 fluid volume injected (see Figure **14**).

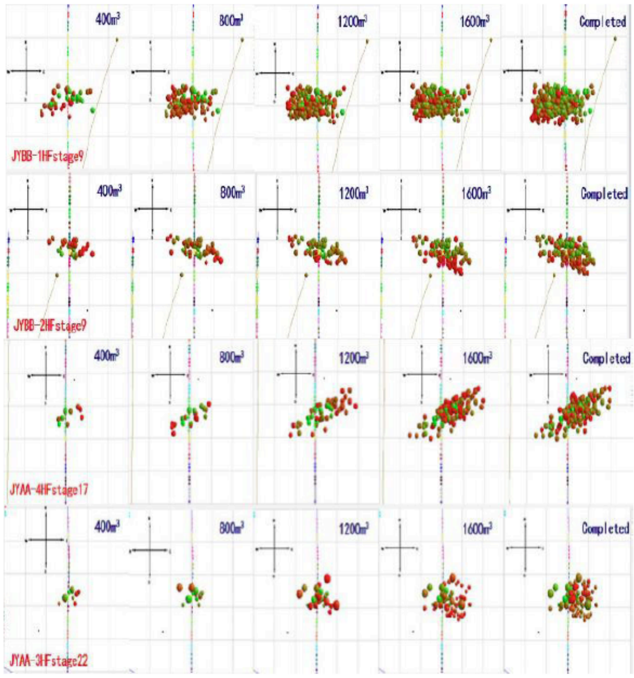

Figure 13: Artificial fracture network propagation with different fluid injection.

On the whole, it's the best time to take aggressive method to make the network more complexity during 900 to 1600m^3, and it has been proved that the present 1800m^3 fluid volume is adapted to the Fuling shale gas development.

3. OPTIMIZATION MEASURES AND THE EFFECT OF APPLICATION

3.1. Amplifying the Interval Appropriately

The segmented measures on the horizontal well section in the shale gas formation aims to enlarge the modified volume and improve the complication degree of fracture. The key point to determine the formation of complicated fracture is the proper segmented designation for horizontal well section and the fracture turning stimulated by the stress change in the fracturing process [4].

The average section intervals of most wells are ranged from 30 to 35 m (see the right side columns in Figure **15**) according to the statistical calculation of the JY AA-BB platform. By the overlapping statistics of the micro-seismic incidents among different well sections in the fracturing process, the results show that most of the overlapping sections lies in JY AA-BB platform, the overlapping width distributes variously from 30 to 139 m, most of which is about 50 m.

Taking Well AA-3HF, a typical well, as an example, the production well testing were conducted under the 2 working conditions of 100000m^3 and 140000m^3 respectively. By analyzing the overlapping proportion of the modified volume between the adjacent two segments and the contribution ratio of different fracturing segment, the results show: the single segment can obtain relatively high gas output when the

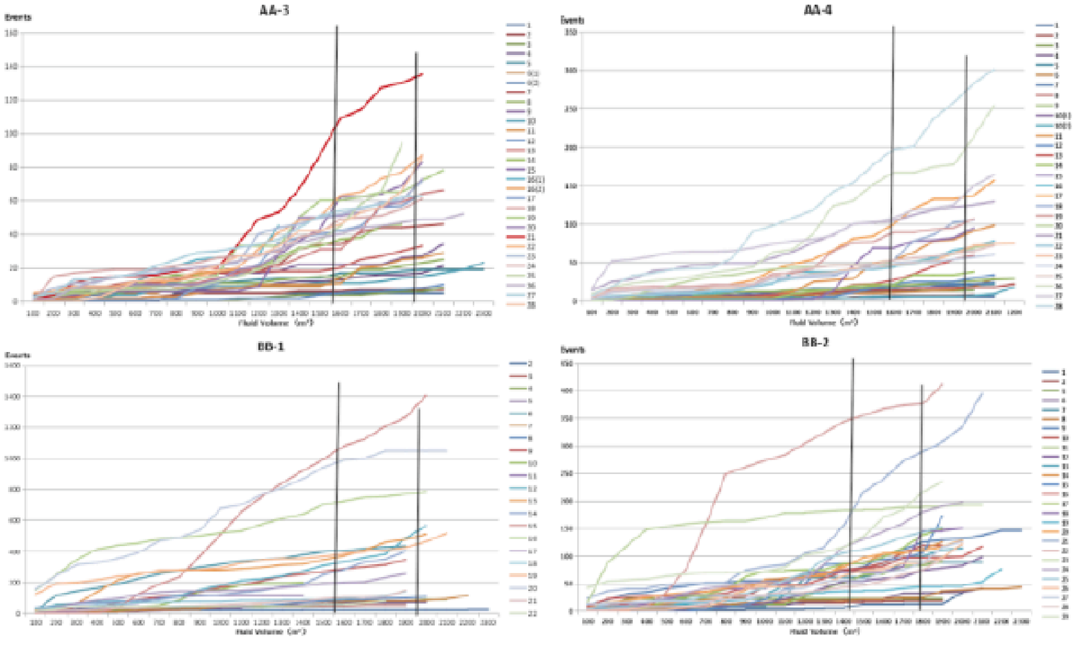

Figure 14: Comparison between micro-seismic events and fluid volume in different stages.

overlapping proportion of the modified volume lies in 6%-12%. By the preliminary screening, the optimized segmental interval is 35-40 m. Therefore, the average segment interval inside the platform are increased to 35-40 m when giving the scheme of Platform CC (see Figure **16**, the red columns left side are the 5 wells in Platform CC, the blue columns right side are the 4 wells in Platform AA-BB).

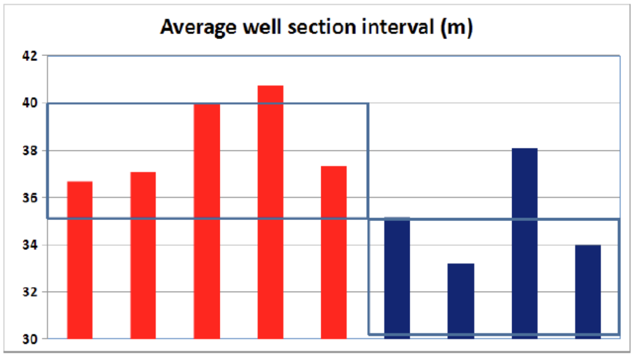

Figure 15: The comparison diagram of the average well section interval in JY Platform CC, AA, BB.

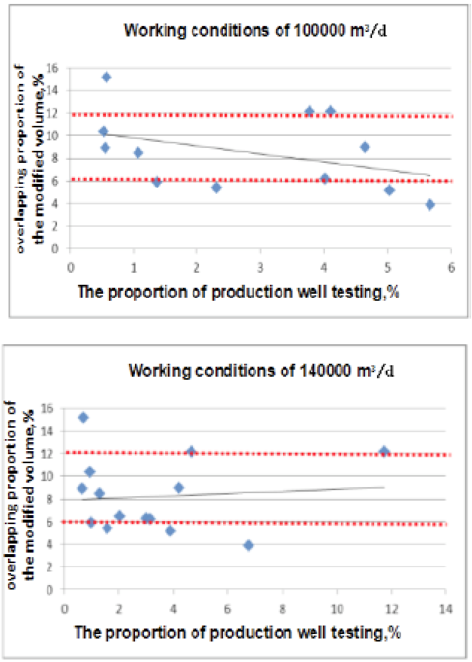

Figure 16: schematic of the relationship between testing results of Well JY AA-3HF and overlapping proportion of the modified volume in the adjacent segments.

3.2. Evaluation Index of Perforation Locality

After the determination of stage interval spacing in the horizontal wells, it's necessary to pick up the perforation locality. Fuling shale gas field has formed a Geology and Engineering Double Sweet Point perforation preference technology [5].

The comprehensive evaluation criteria are porosity greater than or equal to 4.0 %, TOC greater than or equal to 2.0 %，quartz volume content greater than or equal to 30 %, density less than 2.65 gram per cubic centimeter and clusters in a stage stress difference is very small.

The micro-seismic monitoring results show that the higher the GR value is, the smaller the micro-seismic event is, so as the SRV. The region with the higher Young's modulus, the more events and prone to crack fractures and there may be lithology at the Young's modulus mutation site changes, fracturing prone to produce bedding fractures.

Based on the comprehensive evaluation criteria after the fracturing JY AA-BB well groups, we optimize the perforation locality take into account of lower GR value and higher Young's modulus value relatively, Figure **17**.

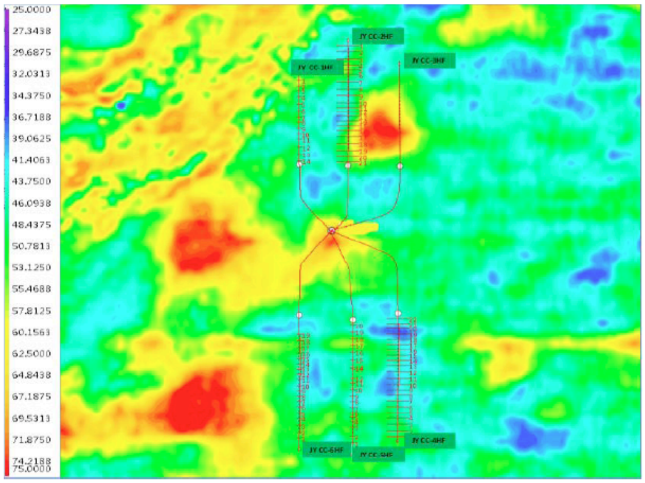

Figure 17: Considering GR and Young's modulus homogeneity of JY CC-4HF perforation locality.

3.3. The Style of Slurry Rate Establishment Optimization at Pretreatment

The effective and efficiency of fracturing are better than JY AA-BB well group during the fracturing construction of CC platform, according to the different layers of the horizontal well trajectory take different style of slurry rate establishment.

JY CC-4HF well trajectory mainly traverses ① layer. We take the style of rapid up slurry rate establishment at pretreatment stage based on the new acknowledge and understanding of micro-seismic monitoring preamble. The whole process was smooth going, sand volume meet the design requirement and fracturing curves present a complex stimulation, Figure **18**.

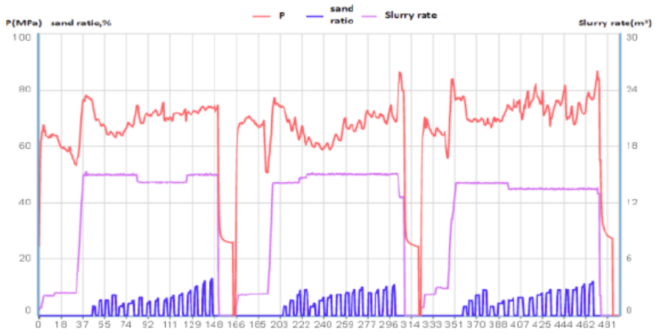

Figure 18: Typical fracturing curves of rapid up slurry rate while through ⊖ layer.

JY CC-1HF well trajectory mainly traverses ③ layer. It also can achieve the expected target by taking the style of step up slurry rate establishment at pretreatment stage (see Figure **19**).

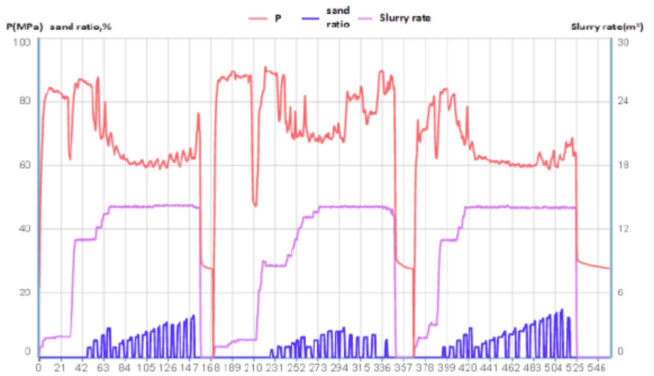

Figure 19: Typical fracturing curves of step up slurry rate while through ⊛ layer.

3.4. Real-Time Optimize of Diversion Process during the Mid-Late Period

With the growth of micro-seismic events, the best time to take aggressive method to make the network more complexity during 900 to 1600m^3 in the construction site. During this stage, in order to improve the net pressure and open new fractures through the implementation of diversion process to temporary block the system of micro fracture network [6], some main diversion process in Fuling shale gas such as ceramicite powder with slick water, low viscosity glue plug and glue plug with ceramicite powder et.al. And the effect is remarkable in the JY BB-CC platform real-time optimization.

For example, when the total fluid volume reached 1065m^3, the first diversion process use ceramicite powder to temporary block the micro fractures at stage 10 of JY BB-2HF, the distribution of micro-seismic events are shown in Figure **20**.

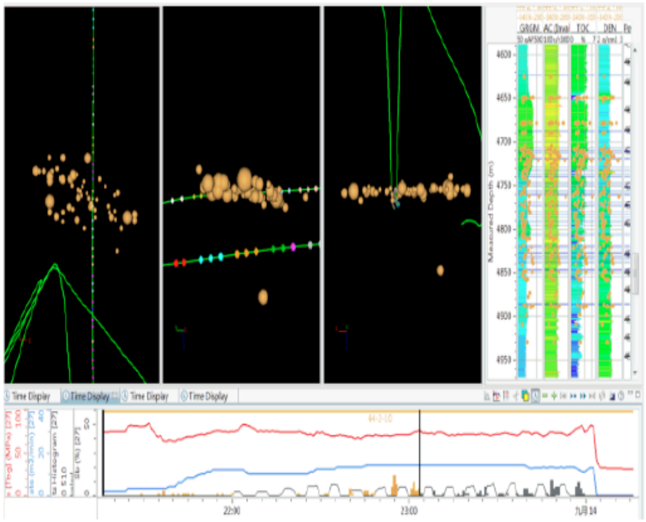

Figure 20: The distribution of micro-seismic events at stage 10 of JY BB-2HF before diversion process.

Compared with the total fluid volume reached 1600m^3, the micro-seismic events distribution show that no obvious change of fracture network geometry before and after temporary blocking, which means the network length, width and height unchanged, Figure **21**. The new events are mainly distributed in the original fracture network and the number of response increase obviously in the east wing after diversion process. This shows that the process is effective and achieve the goal to make the network more complexity.

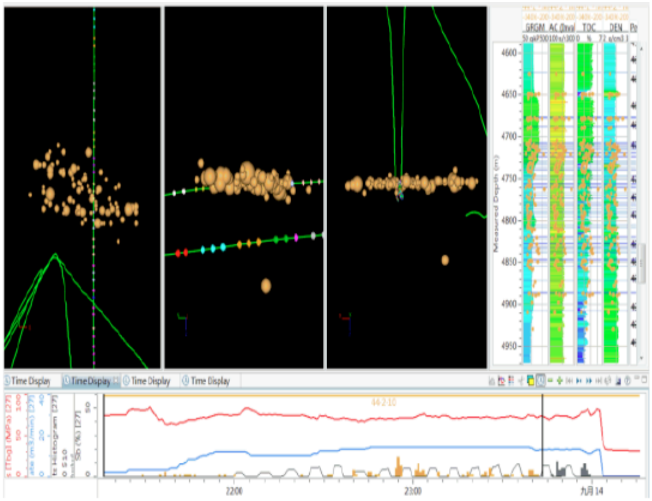

Figure 21: The distribution of micro-seismic events at stage 10 of JY BB-2HF after diversion process.

3.5. Implementation Effect Evaluation

After the fracturing of JY AA-BB well groups, we apply our new understanding of micro-seismic monitoring and fracturing in this paper to the 5 wells of JY CC platform. The optimized fracturing measures had greatly improved the coincidence rate of sand-fluid volume and the efficiency of site construction adjustment. The normalized absolute open flow of 1500 meters has improved obviously and gas test result surpassed the expected level, Figure **22**.

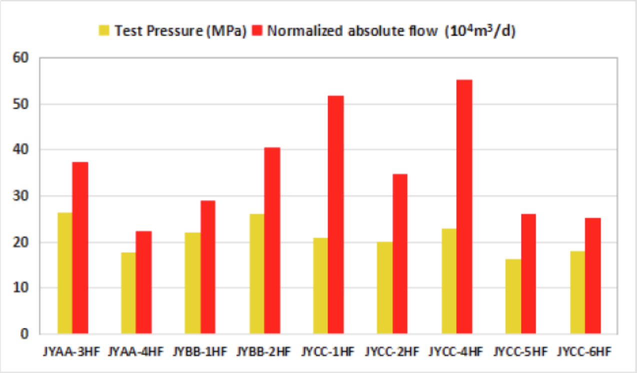

Figure 22: Comparison of normalized absolute flow and test pressure of JY AA-BB-CC platform wells.

CONCLUSIONS

Firstly, the real-time micro-seismic monitoring during the fracturing in Fuling shale gas provides a set of strong reference engineering data for artificial fracture network morphology, geometry and SRV evaluation method, and makes a key role of post-fracturing assessment and optimization of fracturing scheme.

Secondly, the scale and direction of artificial fracture network in shale gas stimulation are greatly influenced by geologic factors. The fracturing design should take into consideration of well trajectory and the properties of reservoir, make full use of seismic, geology and logging data to optimize stage and cluster inter-spacing and perforation locality in order to improve the effectiveness and benefits.

Thirdly, the results show that the pretreatment of different reservoir directly affects the single stage fracturing effect. It's the best time to take aggressive method to make the network more complexity during 900 to $1600m^3$ in the construction site and single stage fluid volume should control in $1800m^3$ more appropriate.

Finally, the application of the new understanding of micro-seismic monitoring in JY CC platform. Through constantly adjust and optimize the fracturing measures to achieve the expected goal of gas test. We strongly suggest to magnify the application in similar areas and geological conditions in the next step.

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