Fracturing scheme design for unconventional reservoirs based on geology-engineering integration method

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Abstract. Horizontal drilling and hydraulic fracturing can effectively increase the contact area between fractures and reservoir, which are important method to realize the economic and efficient development of unconventional reservoirs. In the traditional fracturing scheme design, “sweet spots” guide the fracturing construction. However, due to lack of the interaction process of using engineering data to validate and correct the original data until the final convergence with reality, it cannot be dynamically optimized and matched in time. To overcome above shortcomings, this paper proposes a new network fracturing scheme design workflow based on the integrated geological-engineering integration (GEI) method. The tight carbonate reservoir X layer of oil field A in the Middle East is set as a case. A comprehensive sweet spot evaluation method is established using the partial correlation coefficient analysis method, considering the physical properties and fracturing performance of reservoir. The comprehensive sweet spot model is calibrated and optimized using experimental data, stimulation parameters, well tests, and production data. Based on the comprehensive sweet spot model, the quadrant chart is plotted and varied single well fracturing scheme designs are implemented for different quadrant areas. The numerical simulation results show that it can improve the development efficiency of unconventional reservoirs.

1. Introduction
Unconventional reservoir is an important alternative energy source to conventional hydrocarbon, facing problems such as difficulty in utilization, fast decreasing production, low recovery rate, and high extraction cost [1-3]. Compared to conventional reservoirs, the pore throat scale of unconventional reservoirs decreases from micron to nanometer scale, with strong non-homogeneity and difficulty to describe the sweet spot [4]. To increase hydrocarbon production economically, horizontal wells and network fracturing are required. Accurately identifying the horizontal and vertical sweet spot is a necessary requirement for oilfield development [5]. However, due to the heterogeneity of unconventional reservoirs, reservoir characterization and evaluation need continuous improvement based on constantly updated data of experiments, well logging, stimulation, oilfield production, monitoring, and other technical methods [6-7]. Geology-engineering integration (GEI) method is an...
effective way to characterize and evaluate unconventional reservoir [8-9]. Wu et al [10] proposed the concept of GEI for the first time to solve the problem of difficult characterization and long well construction time for offshore shale gas in southern China. To address the problem of poor accuracy of previous sweet spot prediction models, Jiang et al [11] proposed a "double sweet spot" evaluation model to optimize the number and location of fracturing clusters. In this paper, tight carbonate X layer in A oil field in the Middle East is set as an example, a new network fracturing optimization design process is established based on an GEI method, which dynamically optimizes and matches engineering and geological parameters in a timely manner [12-13], and provides feasible ideas for economic and efficient development of unconventional reservoirs.

2. Fracturing scheme design workflow based on GEI method

For network fracturing, GEI is a dynamic process, which is difficult to achieve with continuous tracking and optimization and dynamic adjustment throughout the whole life cycle of fracturing. The conclusions of pre-fracturing reservoir evaluation need to be systematically verified and timely corrected by data from experiments, fracture inversion and forward progress, and post-fracturing evaluation analysis. Therefore, the well network parameters, fracture parameters and fracture construction parameters matching with geological parameters should also be dynamically optimized and adjusted in a timely manner.

This paper establishes a new fracturing scheme design workflow based on GEI method, as shown in Figure 1, which makes full use of the existing reservoir and stimulation data, and a comprehensive sweet spot evaluation method is established using the partial correlation coefficient analysis method, considering the physical properties and fracture performance of the oil hydrocarbon reservoir. The comprehensive sweet spot model is calibrated and optimized using experimental data, stimulation parameters, well tests, and production data. Ultimately, it makes the model close to the actual reservoir conditions.

Figure 1. The flow chart of fracturing scheme design workflow based on GEI method.

In this paper, tight carbonate X layer in A oil field in the Middle East is set as an example, which can be divided into four small layers from X_1 to X_4 in the longitudinal direction. The macroscopic physical properties of the target reservoir are poor, with porosity distribution ranging from 10.3% to 18.7% and permeability distribution ranging from 0.01 mD to 3.3 mD. Totally, more than 300 wells penetrate the X layer, and 7 wells are put into production. There is a great difference in the effect of increasing production in different wells after reservoir stimulation treatment, due to a lack of targeted fracturing design.

3. Three-dimensional fracability model construction and validation

The typical rock mechanical parameters required for building model mainly include Young’s modulus, Poisson's ratio, maximum and minimum horizontal principal stresses, rupture pressure, and parameters
such as vertical stress and fracture toughness. By building a multivariate neural network model, the transverse wave time difference curves of penetration wells are calculated based on the actual logging data of transverse and longitudinal wave time differences of eight wells and the longitudinal wave time difference logging curves of penetration wells. Based on the longitudinal and transverse wave time difference data, the electrical rock mechanics parameters were calculated. The experimental results of triaxial stress test in the indoor core after dynamic-static transformation are compared with the calculated values, as shown in Figure 2, and the error meets the calculation requirements.

**Figure 2.** Calculated values of logging data are calibrated by rock mechanics experiment.

The rock mechanics parameters were verified by inversion of the fracturing parameters of the fractured wells. Take layer X sand addition fracturing well S as an example, and its fracturing construction parameters are shown in Table 1.

| Parameters                  | Value   | Parameters                  | Value   |
|-----------------------------|---------|-----------------------------|---------|
| Fluid volume (m$^3$)        | 443.1   | Front fluid ratio (%)       | 52.0    |
| Total slurry (m$^3$)        | 39.6    | Pump rate (m$^3$/min)       | 5-5.5   |
| Average Sand concentration (kg/m$^3$) | 277.6   | Maximum sand concentration (kg/m$^3$) | 480.0   |
| Proppant mesh               | 20/40   | Shot thickness (m)          | 55      |

Through the *kinetix* module in Petrel, the temperature-controlled logging, daily oil production, and bottom-flow pressure indicators were fitted to invert the rock mechanics parameters. The inverse rock modulus value is about 1.1-1.3 times of the calculated value of the logs, and the rest of the main parameters, such as the mask layer of the ground stress profile, Poisson's ratio, vertical stress, and fluid, are consistent with the calculation and conventional recognition, etc. The adjusted fitting results are shown in Figure 3. From the fitting results, the fracture length of well S is 114.9m, the effective length is 102.6m, and the fracture height is 67.8m, which is consistent with the logging and production index recognition.

**Figure 3.** The adjusted fitting results of well S. (a) Fracture simulation results. (b) Daily oil production fitting. (c) Bottom of well flow pressure fitting.
4. Integrated sweet spots evaluation model construction and validation

The geology sweet spots can reflect the state of fluid distribution and flow ability in the reservoir, but it cannot reflect the difficulty of fracture reoperation. Therefore, based on the graded evaluation of geology sweet spots, it is necessary to further combine the analysis of rock mechanics parameters, consider the brittleness index, two-way stress difference and fracture toughness and other multi-indicator fracability sweet spots evaluation index, and establish reservoir comprehensive sweet spots evaluation mode, so as to increase the pertinence and accuracy of the reoperation design of the target reservoir, and tap the development potential of the target block to the greatest extent.

The geological engineering sweet spot evaluation method is,

\[ S_G = S_{Gi} W_{Gi} \]  \hspace{1cm} (1)

\[ S_E = S_{Ei} W_{Ei} \]  \hspace{1cm} (2)

Where \( S_G \) and \( S_E \) are geological and fracability sweet spots respectively; \( S_{Gi} \) is the normalized result of a parameter in the set of geological sweet spots parameters; \( W_{Gi} \) is the weight factor of a parameter in the set of geological sweet spots parameters; \( S_{Ei} \) is the normalized result of a parameter in the set of engineering sweet spots parameters; \( W_{Ei} \) is the normalized result of a parameter in the set of engineering sweet spots parameters.

In this paper, \( W_{Gi} \) and \( W_{Ei} \) are determined by the partial correlation coefficient analysis method [14]. This method belongs to statistics, specifically, when studying the influence or degree of correlation of one element in a multi-element system, the other elements are kept constant and the resulting correlation coefficient between two elements is the partial correlation coefficient, which reflects the essential connection between things. Compared with the more commonly used gray correlation analysis and Person correlation coefficient analysis, this method adds the influence of other variables on the variables under study, and can reveal the true correlation between two variables while effectively controlling the influence of other variables. Its calculation formula is.

\[ r_{12(3)} = \frac{r_{12} - r_{13} \cdot r_{23}}{\sqrt{1 - r_{13}^2} \cdot \sqrt{1 - r_{23}^2}} \]  \hspace{1cm} (3)

\[ r_{12(34)} = \frac{r_{12(3)} - r_{14(3)} \cdot r_{24(3)}}{\sqrt{1 - r_{14(3)}^2} \cdot \sqrt{1 - r_{24(3)}^2}} \]  \hspace{1cm} (4)

\[ r_{12(34...n)} = \frac{r_{12(34...n-1)} - r_{1n(34...n-1)} \cdot r_{2n(34...n-1)}}{\sqrt{1 - r_{1n(34...n-1)}^2} \cdot \sqrt{1 - r_{2n(34...n-1)}^2}} \]  \hspace{1cm} (5)

where \( r_{12}, r_{13}, \) and \( r_{23} \) are simple correlation coefficients of two variables, for example, \( r_{12} \) is the simple correlation coefficient of the first and second variables; \( r_{12(3)}, r_{12(34)} \), \( r_{14(3)}, r_{24(3)} \), \( r_{12(34...n)}, r_{12(34...n-1)} \), \( r_{1n(34...n-1)}, r_{2n(34...n-1)} \) are the partial correlation coefficients of the two variables when the control variable is the variable in parentheses. For example, \( r_{12(34)} \) is the partial correlation coefficient of the first and second variables when the control variables are the third and fourth variables.

The evaluation parameters of geological sweet spots mainly include permeability, porosity, oil saturation and effective thickness obtained from well logging interpretation, and the evaluation parameters of fracability sweet spots mainly include engineering parameters such as brittleness index, minimum horizontal principal stress, fracture toughness, etc. Using partial correlation coefficient analysis, some single index classification results are shown in Figure 4, and the resulting established geological and fracability sweet spots classification criteria are shown in Table 2 and Table 3, respectively.
Figure 4. Some single indicator grading results show. (a) Minimum horizontal principal stress. (b) Fracture toughness. (c) Porosity.

Table 2. Summary of single index grading of physical sweet spots based on raw logging data.

| Type of sweet spot | Resistivity (ohmm) | Density (g/cm³) |
|--------------------|--------------------|-----------------|
| III                | >17                |                 |
| II                 | >20                | <2.45           |
| I                  | >25                |                 |

Table 3. Summary of grading of fracability sweet spots list indicators.

| Grade | Britteness index | $\sigma_{\text{min}}$ (MPa) | KIC (MPa·m⁰·⁵) |
|-------|------------------|-----------------------------|-----------------|
| A     | >0.8             | <40                         | <100            |
| B     | 0.65-0.8         | 40-43                       | 100-140         |
| C     | 0.45-0.65        | 43-47                       | 140-220         |
| D     | 0.3-0.45         | 47-50                       | 220-300         |
| E     | <0.3             | >50                         | >300            |

There are 7 wells in the X layer and they were used to verify and calibrate the integrated sweet spot model, and the relationship between their production and the sweet spot zone is shown in Table 4 and Figure 5. For non-fractured wells, when they are in the geological sweet spot zone, most of them have a long stable production period, generally more than 3 years, and the cumulative oil production is high, with wells H, F and J as typical representatives. The fracturing effect of both wells is poor due to the lack of post-fracturing oil supply potential when the wells are in non-physical sweet spot.

Table 4. Correspondence between oil well production and subdivision of sweet spot areas.

| Well | Layer | Geological sweet spot | Fracability sweet spot | Establishment time | Cumulative production (stb) | Production characteristics |
|------|-------|-----------------------|------------------------|--------------------|------------------------------|----------------------------|
| G    | X2    | No                    | No                     | Jun-12             | 6610                         | No stable production period, poor capacity |
| I    | X3    | No                    | Yes                    | Oct-13             | 4300                         | No stable production period, poor capacity |
| H    | X3    | Yes                   | No                     | Apr-05             | 310025                      | 200-300stb/d stable production period: 3-4years. |
| F    | X3    | Yes                   | Yes                    | Aug-12             | 124270                      | 400stb/d, stable production period 3 years |
| J    | X3    | Yes                   | Yes                    | Jun-12             | 136227                      | 400stb/d, stable production period 3 years |
| T    | X3    | No                    | Yes                    | Apr-18             | 5122                        | Significant decreasing capacity after fracturing |
| S    | X2    | Yes                   | No                     | Nov-14             | 62883                       | Significant decreasing capacity after fracturing |
Figure 5. X3 layer engineering and physical sweet spots relative to the well location distribution. (a) The distribution of fracability sweet spots. (b) The distribution of geological sweet spots.

5. Differentiated fracturing program design

Based on the comprehensive consideration of geological and fracability sweet spots, four possible sweet spots combination modes are further divided to clarify the production characteristics of different zones after fracturing under the same fracturing scale, so as to obtain the fracturing adaptability and transformation direction of different zones and carry out zonal fracturing optimization, and then form a differentiated reoperation strategy, as shown in Table 5.

Table 5. The retrofitting strategies under different sweet spot combination modes.

| Order | Geological sweet spot | Fracability sweet spot | Design                           |
|-------|-----------------------|------------------------|----------------------------------|
| 1     | Yes                   | Yes                    | Small-scale fracturing transformation |
| 2     | Yes                   | No                     | Medium-scale temporary plugging fracturing |
| 3     | No                    | Yes                    | Large scale intensive cutting fracturing |
| 4     | No                    | No                     | Abandon                           |

Based on the principle of integral fracturing scheme and development idea, the differentiated integral fracturing scheme design is carried out based on the geological sweet spots and considering the distribution of fracability sweet spots, and the following two integral fracturing schemes are designed.

Scheme 1: Target the geological sweet spots and carry out the overall fracturing design for both types of I and II. This scheme takes the oil production potential of the reservoir after fracturing as the main concern, and deploys production wells in zones rich in geological sweet spots to build a certain scale of productivity, while trying to maximize the benefits without the need for larger-scale fracturing inputs. Therefore, zones I and II were selected in reservoir A to carry out the overall fracturing (Figure 6a).

Scheme 2: Targeting the whole reservoir and considering the distribution of geological sweet spots, carry out the overall fracturing design for both types of areas I II III. This scheme fully considers the overall oil production potential of the reservoir, still deploys production wells at the non-geological sweet spots, and relies on the high fracability at the fracability sweet spots to stimulate the post-fracturing productivity of the wells to form a high production scale, but at this time the fracturing input is also close to the economic limit, and the implementation in the field needs to be evaluated carefully. Therefore, zones I, II, and III were selected in the S reservoir for overall fracturing (Figure 6b).

Figure 6. Schematic diagram of the distribution of simulated fractured wells after overlaying geological and fracability sweet spots. (a) Scheme 1. (b) Scheme 2.
As shown in Figure 7, in Scheme 1, a total of 29 horizontal wells are deployed in Zones I and II, with stable production exceeding 44,000STB/D one year, and then enter into a decreasing period, with the degree of recovery of 19% in the main area in 5 years, and the average cumulative production of single wells in Zones I and II is similar at the beginning of production. As the development progresses, the physical sweet spots thickness in Zone II is larger, the oil saturation is better, and the cumulative production of single wells gradually becomes higher; in scheme 2, a total of 38 horizontal wells are deployed in Zones I, II and III, and the steady production exceeds 50,000STB/D for about one year, and then enters into a significant decreasing period, and the degree of recovery in the main zone is 22% in 5 years. The I zone is less disturbed and has the highest cumulative production per well in the late stage, while the III zone has poor oil saturation and the lowest cumulative production per well. Scheme 1 has lower cumulative oil production compared with scheme 2, but the stable production time is long and the degree of decreasing is low, so scheme 1 is recommended.

Figure 7. Comparison of daily and cumulative oil production forecasts for different scheme.

6. Conclusions
(1) In this paper, a new optimized design workflow for networks fracturing based on an geology-engineering integration (GEI) method is proposed. A comprehensive sweet spot evaluation method is established using partial correlation coefficient analysis, considering the geological properties and fracability of oil hydrocarbon reservoirs. The integrated sweet spots model is calibrated and optimized using experimental data, engineering parameters, well testing and production data. Based on the quadrant map of the integrated sweet spot model, a differentiated single well fracturing program is implemented for different zones to achieve reservoir scale fracturing optimization.

(2) Taking the tight carbonate formation X in oil field A in the Middle East as an example, a comprehensive sweet spots evaluation system was constructed using the partial correlation coefficient analysis, in which the geological and geological sweet spots took pore permeability, oil saturation and effective thickness as the basis for sweet spot identification, while the fracability sweet spots took into account Poisson's ratio, Young's modulus, minimum horizontal stress and fracture toughness. The production dynamics of X-layer wells and engineering parameters were used to verify and correct the rationality of the integrated sweet spots. Differentiated single-well operation schemes were implemented for the sweet spots distribution areas in the three quadrants, and the overall fracturing deployment was carried out. Scheme 1 has lower cumulative oil production compared with Scheme 2, but has a long stable production time and low degree of decrease, and Scheme 1 is recommended. The degree of recovery of this option can reach 22% in 5 years, and if production succession is carried out later, the encryption of Zone III can be considered.

(3) The integrated design and implementation of geo-engineering with network fracturing as the core has greatly improved the development benefits of unconventional oil hydrocarbon reservoirs, and is worthy of further promotion and application in the future.

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