Study and application of geology-engineering integration technology in tight thin heterogeneous carbonate reservoir

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Abstract. The marginal block Zana oil field is a typical hard-to-produce carbonate reservoir, thin net pay, poor reservoir physical properties, low pressure, strong heterogeneity, bottom water and gas cap risks coexist, and it is difficult to obtain profitable production in conventional development model. In order to realize its high-efficiency development, research on integrated geological and engineering technology was carried out. First, the static and dynamic data analysis combined with pilot well technology was used to accurately determine the target layer, confirm the material basis and guide the horizontal well orientation optimization; Second, after comprehensive consideration of production, cost, performance feasibility, and management after putting into production, an integrated solution of completion and stimulation was recommended; Third, optimized well trajectory control and cementing quality control, improved the drilling rate of the horizontal section and the cementing quality, created wellbore conditions for subsequent stimulation; Fourth, optimized the stimulation method, the treatment scale and parameters, maximized the stimulated reservoir under the premise of avoiding water and avoiding gas; Fifth, Optimize the formula of acid system and liquid combination system, adopt the gas lift flowing and lift integrated pipe column and assisted technique using coiled tubing and nitrogen, realized rapid backflow in low-pressure wells and reduced the secondary damage of reacted acid. Based on the above research, integrated technology of geological and engineering considered geological, reservoir, completion, and stimulation has been applied 14 wells with a success rate of 100%. The average single well production is 10.7 times that of adjacent wells, the cumulative production exceeded 20 × 10⁴t, achieved significant production and economic benefits, and that all provide a technical reference for the development of similar reservoirs.

1. Introduction

The Zana oilfield lies in northwestern Kazakhstan, and it is now at the mid-late stage of development after development for more than 20 years. Owing to the challenge of stabilizing the production in major blocks, it is imperative to find more reserves in the areas around the field, where carbonate reservoirs belong to typical tight reservoirs with the reserves hard to be recovered. Net pay is as thin as 1.4-12.1
m; the porosity is as low as 4.2-10.4%; the permeability of \((0.02-4.3) \times 10^{-3} \mu \text{m}^2\) is low to extremely low; pore throat radius ranges \((0.03-1.5) \times 10^{-3} \mu \text{m}\); formation pressure maintenance is as low as 45-65%; the reservoirs are 5.6-38 m away from bottom water and 13-23 m away from gas cap; per-well production is as low as 8.1 t/d on the average for vertical wells. It is difficult to accomplish high production and efficient development of such reservoirs through vertical-well separate-zone stimulation and staged stimulation of uncased horizontal wells. There are some feasible techniques and instructive cases of carbonate reservoir stimulation at home and abroad [1-6], but the reservoir properties are better in those areas. In view of the idea of geology-engineering integration in unconventional reservoir development as well as reservoir properties and physical conditions in this field, we perform field tests and application with marked production increase and economic benefit and thus accomplish efficient development of thin tight heterogeneous carbonate reservoirs.

2. Idea of geology-engineering integration
Geology-engineering integration has been widely applied to the development of shale gas, tight oil, tight sandy conglomerate, and deep high-temperature carbonate reservoirs [7-12]. Despite different forms of integration which are related to reservoir properties and geologic setting in each field, the sole objective is to increase per-well production. "Geology" generally refers to reservoir-oriented geologic-reservoir characterization, geological modeling, oil and gas delineation, geomechanics, petroleum reservoir engineering, and reservoir evaluation. "Engineering" refers to the selection, optimization, and implementation of those techniques and solutions related to exploratory drilling, development, and production in the process of field development [13]. With respect to thin tight heterogeneous carbonate reservoirs, we aimed at efficient development of low-permeability thin marginal reservoirs through horizontal-well staged stimulation and started from top-level design to integrate geologic and reservoir properties with the design and implementation of well drilling, completion, reservoir stimulation, and oil recovery. The objective of reservoir stimulation was proration production through large-SRV stimulation and fracture delineation to avoid water and gas breakthrough. Reservoir geology focused on the study of reservoir distribution for wellbore track design and optimization of horizontal section length and stimulation techniques to realize efficient development. Well drilling and completion aimed at reservoir stimulation through penetrating more reservoirs and improving cementation quality.

Geology-engineering integration is more than a technical idea, and it also involves the integration of organization and administration, including interaction and coordination of relevant administrative authorities, technical sections, service companies, and construction teams. It is necessary to conduct effective communication, unified management, and cooperation to ensure the implementation of integrated technologies.

3. Practice of geology-engineering integration

3.1. Reservoir geology
The zone of interest is tight reservoirs with the reserves hard to be recovered around the major blocks, which feature small net pay, low porosity, low permeability, and small distance to gas cap and bottom water. It is difficult to realize efficient development of such reservoirs through vertical-well separate-zone stimulation. Reservoir geologic research is among the key techniques in integrated studies, the heart of which is remaining oil distribution and reservoir distribution. This is the basis of reservoir stimulation, production increase, and subsequent engineering proposal optimization.

The practice is detailed as follows. The first was to integrate seismic data, log data of neighboring wells, production profiles, production performance, and other reservoir prediction techniques to tentatively establish reservoir and remaining oil distribution and geologic sweet spots. The second, based on numerical studies and the impact of reservoir stimulation on production, was to decrease the lower porosity limit of effective reservoirs from 8% to 4% to expand the definition of reservoir in the zones of interest. The third, based on geologic and reservoir investigation and pilot-hole information, was to further establish the thickness and extension of the zone of interest in the horizontal section and the
distance to gas cap and bottom water because the effect of reservoir stimulation is related to net pay and petrophysical properties. Reservoir stimulation aimed at stream diversion in the thick zone with good petrophysical properties and long fractures in the thin zone with poor properties. The distances between the zone of interest and edge water and bottom water affect the way of stimulation and parameter optimization; the principle of fracture geometry and stimulation parameter optimization was not to connect gas cap and bottom water with the zone of interest. The fourth was to generate transverse fractures to increase stimulated reservoir volume with acid-etched fractures to the greatest extent and ensure the horizontal section track perpendicular to or nearly perpendicular to the major principal stress [14]. Through above geologic and reservoir investigation, we established and direction and limit of subsequent engineering plans.

3.2. Well drilling and completion techniques

3.2.1. Integrated optimization of completion and stimulation. With respect to three points, i.e. proved well drilling techniques, staged stimulation, and borehole conditions for future downhole operations including well workover and water detection and shutoff, the study of well drilling and completion techniques aimed at optimizing casing programme after determining how to perform completion and stimulation. There are three methods of horizontal well completion, i.e. open-hole completion, screen pipe completion, and casing cementing completion. Proved techniques for horizontal-well staged stimulation include open-hole packer segmentation, packer + ball-type sliding sleeve, dual-packer, coiled tubing, bridge plug segmentation, and cementing sliding sleeve. The candidates in different completion conditions and their advantages and disadvantages are shown in Table 1.

The principles of optimization included (1) maximizing per-well production for efficient development, (2) reverse design of stimulation and supporting completion techniques based on production targets, (3) proved techniques with as few subsurface tools as possible, (4) safe operation with small risks, (5) allowing for subsequent water detection and shutoff, and (6) low cost of operation. According to these principles, our first choice was casing cementing completion + coiled tubing and abrasive perforating + bottom packer and staged acid fracturing. Using casing completion, it is possible to effectively compart the reservoirs to be stimulated and perform future water detection and shutoff in spite of small distance between the zone of interest and bottom water. Coiled tubing and abrasive perforating + bottom packer and staged acid fracturing deal with as few subsurface tools as possible in a simple operating process. Abrasive perforating using coiled tubing could be directly followed by annulus fracturing; such a combination features large-displacement operation and small risks. Owing to the exclusion of conventional horizontal-section perforation, the overall cost could be reduced.

3.2.2. Well track control. Owing to carbonate heterogeneity and the location outside the major block, it is important to drill the horizontal section without obstacles and penetrate more reservoirs in the zone of interest. Therefore, we adopted rotary geo-steering + neutron porosity logging while drilling + edge detection. The horizontal section in the thin oil layers of 1.4-6.1 m thick was extended to 1200 m; 83.9% of reservoirs, increased from 38%, were penetrated.

All the drilling tools will be rotated after using the rotary steering system; this could improve the precision and flexibility of well track control and penetration rate, reduce the number of trips, and make borehole clean. The wellbore will become more regular and smooth. Using geo-steering, it is possible to conduct real-time evaluation and correlation of geologic parameters and then adjust well track in real time to penetrate the zone of interest and more reservoirs in the horizontal section.

3.2.3. Cementation quality control. Cementation quality is directly related to the feasibility of staged stimulation. If the casing pipes could be tripped in successfully, high cementation quality is crucial to subsequent reservoir stimulation. To ensure effective segmentation and plugging of the horizontal section, several methods were used to improve cementation quality at the horizontal section. The first was wiper trip using single-centralizer, dual-centralizer, and tri-centralizer pipe strings to ensure that
completion strings could be tripped in successfully. The second was wellbore lubrication, after smoothing and cleaning the wellbore, using 40 m³ drilling fluids composed of original mud, fluid lubricants of 3-7%, and plastic pellet of 1-2% to lubricate the horizontal section and reduce the frictional resistance of borehole wall. The third was to install a roller centralizer every two casing pipes at the horizontal section. The fourth was toughened anti-channeling mud injected into the horizontal section to improve the toughness of cementing mud and its resistance to impact. Swelling agents and agents to avoid trip gas were utilized to improve cementation quality at the reservoirs with high gas-oil ratio. The fifth was washing fluids and spacer fluids to improve displacing efficiency [15].

| Completion method       | Stimulation method                      | Advantage                                                                 | Disadvantage                                                                 |
|-------------------------|-----------------------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Open-hole completion    | (1) Towed acid treatment using coiled tubing (2) Open-hole packer + ball-type sliding sleeve | (1) Large flow area and good connectivity between reservoirs and wellbore (2) Good behavior of segmentation (3) Open and close sliding sleeve as needed to accomplish separate-zone recovery (4) Lowest cost of completion | (1) No borehole wall supporting (2) Many packers in the open hole, which are difficult to be tripped in (3) Challenge of workover treatment, e.g. water detection and shutoff, in the producing interval (4) Challenge of repeated stimulation |
| Screen pipe completion  | (1) Towed acid treatment using coiled tubing (2) Pin-point acid treatment using coiled tubing | (1) Large flow area and good connectivity between reservoirs and wellbore (2) Borehole wall supporting to avoid wellbore collapse (3) Short job cycle and small risks (4) Low cost | (1) Challenge of staged stimulation (2) Challenge of workover treatment, e.g. water detection and shutoff, in the producing interval |
| Casing cementing completion | (1) Packer + ball-type sliding sleeve (2) Dual-packers (3) Hydraulic jetting using coiled tubing + bottom packer towing (4) Bridge plug segmentation (5) Cementing sliding sleeve | (1) Staged stimulation (2) Possible for workover treatment, e.g. water detection and shutoff, in the producing interval | (1) Long job cycle and high cost of completion (2) Reservoir contamination by mud (3) Requirement of high cementation quality (4) Relatively high cost |

### 3.3. Reservoir stimulation
After well cementation with high quality, optimized design of reservoir stimulation became the top priority. The objective was to realize production targets. In accordance with numerical simulations, economic benefit, and heterogeneity of the horizontal section, we followed the principle of individual plan for each section and optimized the design of stimulation methods, operating parameters, fracture parameters, and stimulation fluids to achieve the intended targets.

#### 3.3.1. Stimulation methods and parameter optimization
Reservoir stimulation tests and application began in 2000. Several methods, e.g. acid treatment at the early stage, acid fracturing, hydraulic sand fracturing, and surface sand fracturing with crosslinked acids, have been tested in the field. Acid fracturing has been proved to be the most feasible and effective method for reservoir stimulation and production increase; besides, we learned how to obtain the flow conductivity compatible with reservoir
properties. Therefore, we used acid fracturing for reservoir stimulation in this field, together with large-scale acid treatment in accordance with the relationships between the zone of interest and bottom water, injected water, and gas cap [16-19]. Owing to reservoir heterogeneity, gas-water relation and petrophysical properties of the zone to be stimulated were carefully involved in parameter optimization for each stage. With the prerequisite that gas cap and bottom water cannot be connected, we increased the scale of stimulation and displacement to extend acid-etched fractures as much as possible. Temporary blocking agents were injected into the horizontal section to increase stimulated reservoir volume.

3.3.2. Fracture parameter optimization. With respect to low-permeability reservoirs, hydraulic fracture parameters, e.g. number of fractures, fracture length, and flow conductivity, have a strong impact on post-frac horizontal-well deliverability. As for vertical wells and uncased horizontal wells, we have learned that acid-etched fractures are 70-80 m long and flow conductivity of acid-etched fractures is about $25 \mu m^2.cm$. Our efforts focused on optimizing the number of fractures through numerical simulation to reach the production targets using CMG system. Mesh generation for the whole zone to be simulated was performed using module Grid. Meshes were refined close to fractures, where mesh width was set to be 0.3 m and the flow conductivity was set in accordance with equivalent conductivity. Refer to Table 2 for details, and the model is shown in Figure 1.

| No. | Parameter                              | Value                  |
|-----|----------------------------------------|------------------------|
| 1   | Effective permeability, $\times 10^{-3} \mu m^2$ | 0.5                    |
| 2   | Porosity, %                            | 7.87                   |
| 3   | Net pay, m                             | 7.5                    |
| 4   | Area of simulated cell                 | 1800m$\times$1500m, horizontal well in the center of the cell |
| 5   | Length of horizontal section, m        | 1200                   |
| 6   | Number of fractures                    | 12, 15, 18, 21, and 24 |
| 7   | Fracture length, m                     | 80                     |
| 8   | Fracture flow conductivity, $\mu m^2.cm$ | 25                     |

Fig. 1 Horizontal wells staged fracturing geological model

The reservoir of interest is buried at 2560 m in the Carboniferous System; net pay is 7.5 m; the horizontal section is 1200 m long; present formation pressure is 13.5 MPa; the temperature at the middle part of the Carboniferous reservoir is 75$^\circ$C. We simulated the deliverability using different numbers of fractures, and the results are shown in Figure 2. As shown in Figure 6, per-well initial production and cumulative production increase with the number of fractures; but the rate of increase becomes small when the number of fractures increases to 21. For the number of 21, the initial production is 148 t/d and one-year cumulative production is 42310 t; this means that the intended targets are reached. After that, the cost of stimulation and operating risks will increase with the number of fractures. Thus, the number of fractures was optimized to be 21 for this well. The same method was used to optimize the number of fractures for additional wells.
3.3.3. Stimulation materials. Stimulation materials should meet the requirements of effective reservoir stimulation. The formulae of acidizing fluids were optimized in accordance with reservoir properties, lithologies, and hydraulic features to meet the requirements of different stimulation techniques. The best candidate for deep large-scale acid fracturing was established to be viscous acids featuring small rate, small filter loss, small friction resistance, and capability of producing long fractures.

![Fig. 2 Production capacity with different fractures](image)

![Fig. 3 Core photograph of conductivity test of gelling acid fracture](image)

Figure 3 shows acid-etched grooves produced using viscous acid fracturing. As shown in Figure 4, the flow conductivity of acid-etched fractures decreases with closing pressure and then significantly increases in the area close to the well due to closed fracture acidizing. After closed fracture acidizing, the flow conductivity at large acid displacement is better than that at small displacement. This means that a proper increase in acid volume is favorable for flow conductivity.

![Fig. 4 Comparison of experimental results on conductivity of closed acidizing after gelling acid fracturing](image)
Diverting acids with small damage and good diverting performance were used as the major acidizing fluids for large-scale acid treatment. Fresh diverting acids with small viscosity turn into reacted acids with abruptly increased viscosity after reaction; this gives birth to barriers which will divert subsequent acidizing fluids to other directions. In contrast, reacted acids with small viscosity after gel cracking cause small reservoir damage.

As shown in Figure 5, HCl concentration decline slows down when there are diverting acids injected. The rate of decline for 20% HCl + 5% diverting acids slows down by more than 90%. When the gel in reacted diverting acids comes into contact with subsurface hydrocarbons (e.g. oil and gas), the electrical environment will be changed, followed by micelle damage and gel cracking. Fluids with small viscosity after gel cracking are easy to flow back after operation. In addition, such fluids cause small reservoir damage in view of the rate of core damage of 0.79% on the average.

Foamed acids, which feature small filter loss, concentration decline retarding, cleanup, diverting, and small damage to low-pressure reservoirs, were used as the major acidizing fluids for shallow horizontal-well stimulation. Due to moderate viscosity of foamed acids and dense foam, H+ transmission could be very slow. Thus, acid-rock reaction slows down (Figure 6), and productive reservoirs could be deeply penetrated. Owing to small viscosity and dense foam generated by acidizing fluid reaction, reacted foamed acids are easy to flow back; this further decreases reacted acid damage to reservoirs, especially low-pressure productive reservoirs.

![Fig. 5 Diverting acid Retarding test results](image5.png)

![Fig. 6 Comparison of acid rock reaction rate](image6.png)
Degradable fibrous materials with no reservoir damage and efficient temporary blocking and diverting performance are the major agents in large SRV stimulation. Such materials were mainly used inside the zone to increase stimulated volume.

Viscous acids, diverting acids, foamed acids, and degradable fibrous materials were combined to produce complex liquid-slug stimulation fluids with different viscosities and systems to generate long fractures or fracture network. This guarantees horizontal-well stimulation to the greatest extent in different reservoir properties.

3.3.4. Flow back system optimization. Post-frac flowback management is crucial to reservoir stimulation, especially for low-pressure reservoirs; it is necessary to accomplish quick flowback to reduce formation contamination by reacted acids around the well. Technically, replacing air-lifting discharging pipe strings and integrated lifting pipe strings could ensure quick flowback and production after fluid injection on a large scale. According to the requirements of integrated technology, we used casing-fishing gas-lift valves with 3 ½” drift diameter and high pressure resistance. Base on the theory of variable pressure drop, we increased the depth of air lifting to improve lifting efficiency, flowback rate, and per-well production. Coiled tubing was run into the well with initial low flowback fluid level, and nitrogen gas was injected to assist flowback. With respect to organization and management, our efforts focused on smooth connection between fracturing and flowback operation to reduce time delay in flowback operation. Especially for overseas operation, good organization could give rise to benefit. The flowback system was optimized from two perspectives, i.e. technology and organizational management, to realize quick flowback of fluids and production of oil wells.

3.4. Integrated supporting techniques

3.4.1. Fracture height control. Due to the existence of bottom water and gas cap, it is important to control fracture height. The strategy of large liquid volume and large displacement, which is feasible for shale gas reservoir stimulation, may lead to fracture height out of control and consequent bottom water coning or gas cap gas channeling. To increase stimulated volume and production, fracture height should be controlled jointly in accordance with stress profile, liquidity, and displacement variation. Hydraulic fracture height is mainly related to intra-fracture net pressure. It is hard to control fracture height if the ratio of intra-fracture net pressure to horizontal stress difference exceeds 85%. If the ratio is smaller than 85%, fracture height could be well controlled. With respect to specific reservoir properties, intra-fracture net pressure is closely related to liquid viscosity and displacement. To control fracture height, we adopted small displacement at the beginning to control initial fracture height and increased the displacement at the late stage when the stress difference was reduced through temporary blocking. In addition, acid fracturing using drag reducer with low viscosity at the initial stage may also facilitate fracture height control [11, 20].

3.4.2. Pressure limiting without displacement limitation. In the case that it is possible to conduct large-displacement stimulation in the reservoir conditions, we adopted the strategy of increasing displacement step by step and limiting wellhead pressure to simultaneously ensure large-displacement stimulation and pipe string and wellhead safety. The wellhead pressure was limited within 70 MPa, and the displacement was raised as much as possible. According to operation responses, the displacement was adjusted in real time to achieve reservoir stimulation to the greatest extent in existing limited conditions.

4. Field application

Integrated geologic-engineering techniques were first applied to the Zanazour oilfield in 2016 with success. Within 2 years, 14 wells were put into operation with the success rate of 100%. Horizontal section is 730-1200 m long with the average of 1041 m. The number of stages is 14-26 with the average of 19.5. Initial oil production was 54-128 t/d without water; the average production was 87 t/d, which is
10.7 times that of neighboring wells. Cumulative production increase exceeded 20×10^4 t. In view of remarkable production increase and economic benefit, some horizontal wells have been deployed for the development using integrated techniques. Thanks to technical research and lessons learned from related technologies, we established integrated geologic-engineering techniques including reservoir geology, well drilling, and well completion centered on reservoir stimulation to realize efficient development of thin tight heterogeneous carbonate reservoirs.

5. Conclusions
(1) Technically, integrated techniques for the development of thin tight heterogeneous carbonate reservoirs focused on efficient development through horizontal-well staged stimulation. We started from top-level design of integrated well drilling, completion, reservoir stimulation, and oil recovery in accordance with geologic and reservoir properties. Organization and management focused on unified management and cooperation of technical sections, service companies, and construction teams to ensure the effective implementation of integrated techniques.

(2) Thin heterogeneous reservoirs were pinpointed using static and dynamic data and pilot-hole drilling; this laid the foundation for horizontal well track optimization and production increase through reservoir stimulation.

(3) Integrated well drilling and completion focused on the principles and methods of completion and stimulation, well track control, and cementation quality control to penetrate more reservoirs at the horizontal section and improve cementation quality. This gave birth to good wellbore conditions for subsequent stimulation.

(4) Using optimized stimulation design, we accomplished the optimization of stimulation methods, materials, fracture parameters, operation parameters, and flowback in accordance with reservoir properties. It is noted that complex liquid systems with different types and viscosities and large-volume stimulation using temporary blocking and intra-zone diverting maximized the effect of reservoir stimulation and increased petroleum production and per-well estimated reserves. Fracture height was properly controlled to avoid water and gas breakthrough. Optimized flowback system ensured quick fluid flowback with high efficiency.

(5) Integrated geologic-engineering techniques were successfully tested and applied to thin heterogeneous carbonate reservoirs with low permeability, and we achieved efficient development with remarkable production increase and economic benefit. Our study casted light on the development of such marginal reservoirs.

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