The Study and Application of In-situ stress Distribution in Ultra-deep Fractured-caved Carbonate Reservoirs

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Abstract. There are abundant oil and gas resources in carbonate reservoirs of Tarim Basin, and more than 90% come from fractured-caved carbonate. These fractured-caved reservoirs are formed by the superposition of large fracture zone and karstification. The fractured-caved bodies generally appear in strips along the fracture zone and are distributed irregularly in vertical and horizontal directions. In addition, the ultra-deep burial (6500-7500m) leads to strong heterogeneity of the reservoirs. This paper presents using horizontal wells to cross the fractured-caved bodies is an effective means to improve the economic profit of oil and gas field development. Based on geomechanical study, the development mechanism of high-quality fractured-caved bodies can be determined, the contradiction between multiple fractured-caved bodies and safe drilling can be solved, and the reservoir stimulation plan can be optimized. The study can provide quantitative data basis for well trajectory optimization, prediction of drilling safety window, determination of maximum build-up slope in deviated section, how to use one well to cross multiple fractured-caved bodies and optimization of reservoir stimulation program. The results show that the ultra-deep carbonate reservoirs are affected by four factors: faults, fractures, irregular karst and in-situ stress, resulting in strong heterogeneity and anisotropy of reservoir. Therefore, the probability of high-quality fractured-caved bodies encountered by well trajectory drilling in different directions and depths is different, and the stability of wellbore in different directions and deviation is also different. When the drilling trajectory crossed the fault zone, it experienced a large range of in-situ stress, so the stimulation effect varied greatly in different well sections. The geomechanical study of ultra-deep carbonate reservoirs shows that the strike of the fault is similar to the present in-situ stress, and it is easier to develop high-quality fractured-caved bodies in relatively weak stress environment. Through the study of the relationship between fracture system and in-situ stress, it provides a method to optimize the well trajectory in consideration of both high-quality reservoir and drilling engineering safety.

On the basis of optimizing the best well trajectory, it can predict the safe drilling window more accurately, guide drilling through multiple fractured-caved bodies as much as possible, and implement reservoir stimulation effectively, laid a foundation for high-quality and high-yield drilling. So far, three carbonate reservoir oilfields’ 3D stress modelling have been completed and applied to well placement, drilling and development. The average oil production per well exceeds 300 tons under 6mm nozzle conditions.

1. Introduction
The carbonate reservoir in the Tarim Basin is buried very deep (6500–7500m) and high-pressured(50–70MPa) karst fractured-cavernous reservoir. Its heterogeneity is very strong, and its matrix, whose porosity is low, basically does not have the storage capacity. Fractures and caves are the
main storage space and flow channel, in which the performance of the fluid is pipe flow (Li Y et al. 2013). Using horizontal wells to cross the fractured-caved bodies is an effective means to improve the economic profit of oil and gas field development. However, the horizontal well drilling faces the challenge of complex geological background. There are three main problems: (1) How can the horizontal well track through the reservoir with good permeability? (2) How to ensure the best wellbore stability? (3) How to optimize the reservoir stimulation plan?

In this study, a geomechanical study of ultra-deep carbonate reservoirs was carried out, to make clear the development mechanism of high-quality fractured-caved bodies, solve the contradiction between multiple fractured-caved bodies and safe drilling, and further optimize the reservoir stimulation plan. Firstly, the influence of ancient stress evolution on the present strike-slip fault pattern was analysed from structural deformation. Secondly, the magnitude and direction of present in-situ stress were determined based on borehole traces and various logging data, and its distribution in 3D were analysed, so as to determine the interaction between strike-slip fault system and in-situ stress (Chang Chandong, 2014). Thirdly, it provides quantitative data basis for well trajectory optimization, prediction of drilling safety window, determination of maximum build-up slope in deviated section, how to use one well to cross multiple fractured-caved bodies and optimization of reservoir stimulation program.

2. Geological background

With the exploration and development of Ordovician carbonate in Tarim Oilfield, Tabei uplift and central uplift of Tarim Basin have gradually formed a contiguous trend, and the oil and gas situation is clear, which has become one of the main sources of carbonate crude oil production. The important resource replacement areas for realizing the connection of Tazhong and Tabei are Yuemanxi, Yueman, Fuyuan and other blocks located in the southern margin of Tabei. The main reservoir type is fractured-cavernous reservoir. According to the relationship between faults and reservoir distribution, it is further defined as "fault solution" (Ni Xinfeng et al. 2009). However, due to the complex structure inside the fault solution, the fractured-caved carbonate rock is the main reservoir type, On the other hand, due to a variety of factors, the formation of the Ordovician O3tr formation, Yijianfang Formation and Yingshan formation in the structural belt appears abnormal high pressure, drilling problems are increasing day by day, and well completion measures is lack of quantitative optimization basis, which affects the exploration discovery and production (Wang Zhaoming et al. 2009).

The inner structure of "fault solution" can be divided into four types (I, II, III and IV in the figure represent different fractures and caves), which are plane fractures and caves combination type (Fig. 1a), inclined fractures and caves combination type (Fig. 1b), vertical fractures and caves combination type (Fig. 1C) and irregular fractures and caves combination type (Fig. 1D). The distance between caves ranges from 0.1 M to 5 m, and those with a distance greater than 20 m are regarded as another fault solution.

![Fig.1 Four styles of fractured-vuggy carbonate reservoir from outcrops](image-url)
Due to the complexity of the internal structure of fault solution, the drilling rate of reservoirs in the southern margin of Tabei is low. On the other hand, in the drilling of the non-target layer of the Ordovician O3tr formation and the target layer of the Ordovician Yijianfang Formation and Yingshan formation have been encountered abnormal high pressure one after another, which has brought complexity to the drilling and delayed the exploration and development to a certain extent (Yang et al. 2012).

3. Relationship Between Stress and Fracture

The slope with gentle inclination and weak fold deformation becomes a relatively stable paleostructural unit between the north of Tarim and the middle uplift. The depth of carbonate reservoir is nearly 8000 meters, the vertical stress is dominant (nearly 200MPa), and the normal fault stress mechanism ($SV > shmax > shmin$). In the whole zone, the structural stress is weak, the regional stress distribution is relatively homogeneous, the horizontal stress difference is smaller ($< 10MPa$), and the regional stress direction is north-east. The interaction between large structure, fault and stress is shown in Figure 2. As shown in Figure 2, the distribution diagram of the minimum principal stress in Yijianfang formation is shown. The disturbance of the stress field corresponding to the fault is obvious in the figure. The stress field near the fault is higher than that around. Then, the relationship between stress and fracture is studied and the stress distribution can be clear, which is helpful to prediction of pre drilling pressure (Zoback, M. D.et al. 2007).

![Shmin Stress Distribution](image)

Fig.2 Minimum horizontal principal stress distribution plan of Yijianfang Formation in Guole

4. Well Deployment and Well Trajectory Optimization

Yingxi-1 well is a pre exploration well deployed in the southwest wing of yingmai-2 anticline in the south of Yingmaili low uplift in Tabei. The purpose of drilling is to explore and evaluate the oil and gas bearing property of strike slip fault in the west of yingmai-2 structure. The high buried depth of the target layer of the well is located in the environmental protection zone, and the area where well
points can be set is located in the north of the environmental protection zone. It is necessary to optimize well point and well trajectory to lay a good foundation for successful drilling.

According to the analysis of drilled wells in Yingmai 2 anticline, the main stress direction in this area is NNE 20°. According to the stress mechanism of normal fault type in the area, the stability of inclined well in Ordovician target layer is better than that of vertical well, and the stability orientation is NWW 290°± 35°, SEE 110°± 35°. In addition, according to the occurrence information of natural fractures picked up by drilling in the area, it is predicted that the orientation of natural fractures with good permeability is basically consistent with the wellbore stability (Jin Yan et al. 2004), and it is preliminarily determined that the two directions of northwest and southeast are favorable well trajectory (Zoback, M. D.et al. 2012; Knipe, R.J.1992). Combined with the distribution of environmental protection areas, the final drilling azimuth of the well is 157°, the deviation is 86°. It can not only ensure that the wellbore passes through the natural fractures vertically at a large angle, which is conducive to the formation of complex fracture network in well completion transformation, but also conducive to the well stability. This direction is also vertically passing through the NE-SW strike fault, which provides guarantee for the smooth drilling to the fault solution, and avoids the surface environmental protection area.

![Fig.3 Optimal well trajectory diagram of well Yingxi 1](image)

5. The Solution of the Instability of Drilling

West Guole area is located in Fuman Oilfield on the South Bank of Tahe River. Of the 65 wells drilled in this oilfield, 24 wells are complicated to varying degrees in the non-target formation of Permian Silurian system, especially lost circulation and sticking. The maximum loss of drilling fluid is 1697m³. With the loss of drilling fluid, the wellbore block falls and the stuck drilling occurs. Through analysis, it is found that the wells where lost circulation occurred are mainly distributed in the parallel faces zone, subparallel faces zone and blank faces zone, especially the blank faces zone. According to the analysis of drilling wells, the lost circulation layers are distributed in Permian, Carboniferous and Silurian, with the most serious in Permian. The high-speed change area at the top of Permian, the transition area of faces belt change, the low-speed clastic rock section at the lower part of Permian, and the area with large changes in lithology and velocity in Permian are the areas with high lost circulation. The main reason is that the blank faces belt is rich in fractures joints and pores are mainly dacite (Wu Guanghui et al. 2012). When drilling into the lower Carboniferous Silurian strata, the main mechanism of drilling complexity is fault development. When drilling in the fault fracture zone, the leakage occurs, and causes the borehole wall to fall. The closer to the fault, the more serious the leakage is, and the more frequent the stuck drilling is.

Based on the above research, the concept of "design highly deviated wells / horizontal wells to avoid shallow fractures and reduce drilling well control risk from the source of geological design" is proposed for wells with blank faces. Based on the seismic coherence property and the characteristics of the vertical in-phase axis, the plane distribution area and the vertical fault crossing horizon of the fault are identified, and then the three-dimensional stress field model is established to clarify the influence of different occurrence faults on the wellbore stability (Johri, M., E. M. et al. 2013).
Combined with the distribution orientation of the natural fracture activity in the reservoir, the wellbore location and well trajectory orientation are optimized. According to previous studies, the Guole block is relatively stable bedrock 130 meters away from the fault core. Based on this, the approximate location of surface well points can be determined, and the regional principal stress orientation is NE-SW direction. Therefore, the orientation of wellbore stability and the distribution orientation of permeable fractures are NW-SE direction (Fisher, Q.J. et al. 2001). At the same time, considering the vertical crossing of fault solution, it is conducive to the later transformation to increase the diversion area. The four wells deployed in the area are all short radius horizontal wells, and the drilling direction is NW-SE, which can smoothly drill through complex formations and provide guarantee for oil and gas discovery.

6. Classification Method and Application of Well Completion

The goal of geological engineering integration is to realize the exploration discovery and oil and gas production in this area, and to realize safe and efficient drilling and cost control. On the basis of geological and geophysical fine characterization, well point optimization and well trajectory optimization are carried out. After drilling, the evaluation of geomechanical parameters is strengthened. Combined with the actual drilling situation of the reservoir, the classified production improvement scheme of complex carbonate fractured vuggy reservoir is established. After completion of drilling, geomechanical evaluation is carried out. According to the distribution of stress field around the well, reservoir calibration results, wellbore collapse, natural fracture development and the relationship between them, the production improvement scheme of the well is determined. The first type is to drill into the reservoir and put it into production directly. The second type is to drill above the reservoir and continue drilling by deepening or deepening side tracking if it does not enter the main reservoir. The third type is to drill to the reservoir boundary and analyse the matching between the in-situ stress orientation and the reservoir orientation. The main reservoir can be communicated through fracturing, and the fracturing method is adopted and the fracturing scheme is quantitatively optimized to achieve high oil and gas production. The fourth type is when drilling outside the reservoir, and the orientation of in-situ stress does not match the main development orientation of the reservoir,
so it is impossible to communicate with the reservoir through acid fracturing and other measures, then side tracking is directly carried out, and the trajectory of side tracking is optimized to realize oil and gas discovery.

7. Conclusion

In the middle Caledonian period, large-scale NE and NW strike-slip fault systems were formed under the in-situ stress compression of NE and SN directions. In the following three stages of tectonic movement, the faults in these two directions were inherited and developed. At the same time, the deep hydrothermal solution poured into the fault system, which accelerated the dissolution of carbonate reservoirs at the fault location.

According to the analysis of several drilled wells, the present maximum horizontal principal stress in this area is mainly in NE direction, and the in-situ stress state is normal fault, in which the vertical stress $\sigma_v = 2.48\text{SG}$; the maximum horizontal principal stress $\sigma_H = 2.0-2.20$ SG , and the minimum horizontal principal stress $\sigma_h = 1.70-1.90\text{SG}$.

On the whole, the study area belongs to the platform basin area with relatively gentle structure and weak fold deformation. The present in-situ stress field is relatively simple from a macro view. The vertical stress in the super deep is dominant, the tectonic stress is weak, and the regional stress distribution is relatively homogeneous.

In the fracture cave system, due to the influence of strike-slip faults, the distribution of in-situ stress becomes more complicated. The orientation of the maximum horizontal principal stress will deflect along the strike of the main fault, the anisotropy of in-situ stress around the fault zone will increase, and the in-situ stress between the fault zones will fluctuate. In the same fault zone, the stress in the tension section is the lowest, the stress in the translation section is higher, and the stress in the compression section is the highest.

The ultra-deep carbonate reservoirs are affected by four factors: faults, fractures, irregular karst and in-situ stress, resulting in strong heterogeneity and anisotropy of reservoir. Therefore, the probability of high-quality fractured-caved bodies encountered by well trajectory drilling in different directions and depths is different, and the stability of wellbore in different directions and deviation is also different.

When the drilling trajectory crossed the fault zone, it experienced a large range of in-situ stress, so the stimulation effect varied greatly in different well sections. Therefore, it is necessary to optimize the stimulation program according to the in-situ stress and the distribution of natural fractures.
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