Study on the mechanism and main control factors of lost circulation in deep brittle shale in Changning block

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Abstract. Sichuan Changning block is rich in shale gas resources reservoirs, but the lost circulation problem is prominent during the horizontal drilling process of deep shale gas wells, which seriously restricts the exploration and development of deep shale gas resources in the Changning Block. Aiming at the problem of lost circulation in the drilling process of deep shale gas in Changning well area, the difference of the vertical and horizontal distribution of lost circulation is clarified by comparing the information of deep shale lost circulation in this block. Based on single well logging data and 3D seismic interpretation, the 3D distribution model of shale gas formation fracture, in-situ stress and formation pressure was established. The response relationships among fracture development, in-situ stress distribution, formation pressure and lost circulation in shale formations were studied, and the lost circulation mechanism and main influencing factors of deep shale gas formations in the Changning well area were clarified. The results of the study show that deep shale lost circulations in the Changning well block is prominent and widely distributed longitudinally and horizontally with unclear regularity, and that regional fracture development, in situ stress field and formation pressure have obvious effects on well leaks. The distribution of fractures, in-situ stress field and formation pressure in Changning block have a significant and highly responsive effect on lost circulation. The results of this paper reveal the complex mechanism of deep shale lost circulation in the Changning block and the main influencing factors, and provide a certain scientific basis for prevention and treatment of deep shale reservoir leakage in Changning block.

1. Introduction
The frequent occurrence of lost circulation during drilling in Changning well area is an important reason to hinder the efficient development of shale gas. In 2020, a total of 305 lost circulations occurred in Changning well area, with a total loss time of 766.56d. The frequent occurrence of lost circulation in Changning block is characterized by complex mechanism, large amount of loss and longtime loss, which has a serious impact on the economic and time cost of shale gas development [1].

The key to improve the efficiency and success rate of leakage treatment is to find out the mechanical mechanism and properties of leakage [2]. For the study of lost circulation mechanism and main influencing factors. In 2011, Wang G et al. [3], the theory and method of rock fracture mechanics were introduced in the analysis of lost circulation control mechanism, which revealed the mechanism of preventing the fracture extension induced by plugging of drilling fluid. In 2013, Shen H C et al. [2], put forward a set of lost circulation diagnosis and treatment technical ideas based on the mechanism of lost circulation mechanics, aiming at the complex mechanism of lost circulation in fractured formation, and emphasized the urgency of issuing relevant industry standards for lost circulation plugging operation. In 2016, Li D Q et al. [4], used the Herba model to describe the rheological properties of drilling fluids and established a one-dimensional drilling fluid loss model in the formation with infinite fracture length. The effects of positive pressure difference, fracture width and rheological parameters of drilling fluids on the loss rate and final loss amount were studied. In
2017, Feng Y et al. [5], collected the engineering information of lost circulation in Hangjinqui work area, and made it clear that the mechanism of lost circulation in this work area is mainly the development of formation microfractures and stress sensitivity, which is easy to form fractures and lead to lost circulation. Aiming at the leakage mechanism, the idea of plugging while drilling and plugging by chemical gel under pressure is put forward. In 2019, A W Chan et al. [6], found that the leakage pressure near faults or fault damage zones in some drilling processes is usually lower than the minimum horizontal principal stress. It is proved that the relationship between downhole pressure and fault reactivation pressure is the main cause of lost circulation. The leakage probability is related to the lithology of the damage zone. In 2020, Ren R et al. [7], pointed out that in order to solve the problem of lost circulation and design the best plugging material, we must understand the mechanism of lost circulation and infer the direction of geological or fracture characteristics. In order to solve these problems, a real-time inversion method of fracture width and geological characteristics is proposed. The fracture width is approximately calculated, and then the geological characteristics of lost circulation zone are classified and inferred. In 2021, Tan J Z et al. [8], taking Bozhong 34-9 as an example, clarified the necessary conditions, main driving forces and occurrence process of lost circulation, and put forward targeted leak prevention measures.

Based on single well logging data and three-dimensional seismic interpretation data, this paper will build a three-dimensional distribution law model of shale gas formation fractures, in-situ stress and formation pressure in Changning well area. And combined with the actual lost circulation, the main factors influencing the leakage are explored. The research results will provide strong theoretical and technical support for the follow-up drilling process in Changning well area, and have important significance for the efficient and low-cost development of shale gas in this block.

2. Analysis of lost circulation mechanism and situation in Changning block

2.1. Types and mechanism of lost circulation

Lost circulation is a phenomenon in which a large amount of drilling fluid is leaked into the formation during drilling [9]. Clarifying the mechanism of lost circulation is a necessary prerequisite for successful plugging. Common lost circulation mechanisms in deep brittle shale can be classified into the following types [10-11]:

2.1.1. Fracturing lost circulation. When the pressure in the wellbore exceeds the fracture pressure of the formation, a fractured leakage channel is generated in the formation [12]. The lost circulation pressure prediction model for fractured wells is as follows:

$$p_l = 3\sigma_h - \sigma_h + S_t - \alpha p_p$$  \hspace{1cm} (1)

where $p_l$ is lost circulation pressure, $\sigma_h$ is minimum horizontal principal stress, $\sigma_h$ is maximum horizontal principal stress, $S_t$ is tensile strength, $\alpha$ is effective stress coefficient and $p_p$ is formation pressure.

2.1.2. Closed fracture extended lost circulation. The effective liquid column pressure in the wellbore is greater than the fracture closing pressure and the tensile strength at the end of the fracture, resulting in fracture opening, expansion and extension, resulting in lost circulation [13]. The leakage pressure prediction model of this kind of mechanism is as follows:

$$p_l = \sigma_h - \left(\frac{w_0}{A w_c} - 1\right)^{\frac{1}{\alpha}} (\sigma_h - p_p)$$  \hspace{1cm} (2)

where $w_0$ is crack width without wellbore positive pressure difference, $A$ and $\alpha$ is undetermined coefficient and $w_c$ is leakage width.
2.1.3. **Differential pressure lost circulation.** Fractures can exist in all types of formations encountered by drilling during the drilling process, and are usually highly likely to occur in areas such as tectonic shafts and high points [14]. Lost circulation is generated by drilling fluids entering pore spaces, natural fractures and cavern channels under positive pressure differentials. This type of leakage pressure prediction model is as follows:

\[ p_l = p_v + \Delta p \]

where \( \Delta p \) is leakage channel pressure loss.

2.2. **Analysis of the lost circulation of shale formation in Changning well area**

A total of 20 representative wells in different well areas of Changning block are selected to analyze the distribution of lost circulation in this block from the horizontal and vertical perspectives.

2.2.1. **Analysis of lateral distribution of lost circulation.** Figure 1 shows the lateral distribution diagram of lost circulation frequency and the ratio diagram of lost circulation frequency in different well areas in Changning block.

The analysis shows that the lateral distribution of lost circulation in Changning block is closely related to the topography. The lost circulation frequency in the structural anticline is higher than that in the syncline. The lost circulation frequency in Ning 216 well area located in the structural anticline accounts for 69.5%, and the lost circulation ratio in Ning 201 and 209 well area located in the structural syncline is significantly lower than that in Ning 216 well area. Overall the frequency of lost circulations shows a pattern of low in the middle and high in the surroundings in terms of lateral distribution.

2.2.2. **Analysis of vertical distribution of lost circulation.** According to the statistics of lost circulation times of different formations in each well block (Figure 2 and Figure 3), the complicated vertical distribution of lost circulation is analyzed.

The longitudinal distribution of losses in different well zones is roughly the same. Longitudinal distribution of lost circulation is mainly concentrated in Marine Maokou Formation and Longmaxi Formation shale strata, but the lost circulation situation of Maokou Formation and Longmaxi Formation in Ning 216 well area is more serious than that in Ning 201 and 209 well area. Based on the above analysis, the spatial distribution of lost circulation in Changning block shows obvious vertical and horizontal difference. In the horizontal distribution, the distribution of lost circulation is closely related to the terrain, and the situation of lost circulation in Ning 216 well area is
worse than that in the other two well areas; In the vertical distribution, the lost circulation is mainly concentrated in Maokou Formation and Longmaxi Formation. The lost circulation in Maokou Formation and Longmaxi Formation of Ning 216 well area is more serious than that in the other two well areas.

Figure 3. lost circulation ratio of different layers in different well areas

3. Study on main controlling factors of lost circulation in Changning block

3.1. Three-dimensional distribution law of fractures in Changning block
Fracture is an important reason for the occurrence of lost circulation in the drilling process [15]. Therefore, it is important to predict the three-dimensional distribution law of fractures in Changning block and to explore the mechanism of lost circulation. Based on the existing seismic data in Changning block, the ant tracking technology is used to track and predict the fault fractures in the target area. The fracture prediction results are shown in Figure 4.

Figure 4. fracture prediction results of Changning block

From the results of fracture prediction, it can be seen that fractures are relatively developed in Changning block, and the degree of fracture development around the block is higher than that in the center of the block. In addition, the fracture density in well Ning 216 is significantly higher than that in well Ning 201 and well Ning 209, which may be one of the important factors leading to the relatively serious lost circulation in Ning 216 well area.

3.2. The prediction process of the in-situ field and formation pressure
In-situ stress and formation pressure are also closely related to lost circulation. From the common lost circulation mechanism in shale formation, it can be seen that the size of in-situ stress can determine the formation fracture pressure, so as to determine whether the wellbore is fractured and whether the closed fracture is open. Whether lost circulation occurs in natural fractures depends on the formation pressure. Based on the data of single well in-situ stress and formation pressure, the regional in-situ stress and formation pressure model is established. The model building process is shown in Figure 5:

Figure 5. model establishment process

3.3. Prediction results of in-situ stress field and formation pressure model
3.3.1. Prediction results of in-situ stress field model. Through the above model building process, the in-situ stress field model of Changning block is obtained as shown in the Figure 6 below: It can be seen from Fig. 6 that the size of in-situ stress field in Changning block is closely related to the distribution of stratum structure and stratum burial depth. The strata in the lower part of the tectonic syncline have deep burial and large in-situ stress, and the in-situ stress tends to decrease in the south and north directions. The in-situ stress in Ning 201 and Ning 209 well areas located in the tectonic syncline is higher than that in Ning 216 well area located in the anticline.

3.3.2. Prediction results of formation pressure model. The distribution of formation pressure is similar to that of in-situ stress. The formation pressure of syncline in the center of the structure is greater than that of anticline around the structure. Similarly, the formation pressure of Ning 201 and 209 well area is higher than that of Ning 216 well area due to the factors of structure and topography. The field measured XPT data of Longmaxi Formation was used as validation data to verify the reliability of the prediction model of formation pore pressure. The comparison between the field measured XPT data and the prediction results of the model is shown in Table 1:

![Figure 6. Prediction results of minimum horizontal principal stress](image1.png)

![Figure 7. Prediction results of formation pressure model in Changning block](image2.png)

![Figure 8. Prediction results of formation pressure](image3.png)

| Well name   | XPT measured formation pressure | Model prediction of formation pressure | Accuracy |
|-------------|--------------------------------|----------------------------------------|----------|
| N201H30-2   | 1.30                           | 1.38                                   | 94.2%    |
| N209H66-2   | 1.44                           | 1.61                                   | 89.4%    |
| N216H27-3   | 1.29                           | 1.18                                   | 91.4%    |

Through the verification of XPT measured formation pressure data, the average accuracy of this prediction model is about 91.67%, which has high reliability.

4. Verification of response relationship of main control factors of lost circulation in Changning block

The information and location of 20 lost circulation wells are marked on the plan of fracture, in-situ stress field and formation pressure, so as to explore the three response relationships of lost circulation and fracture, lost circulation and in-situ stress field, lost circulation and formation pressure respectively.

4.1. Verification of influencing factors of horizontal distribution difference of lost circulation

4.1.1. Relationship between fracture development and lost circulation response. Fractured formation is often accompanied by frequent lost circulation. When lost circulation occurs, fractures are usually considered as natural lost circulation channels of drilling fluid. The response relationship between lost circulation and fracture is verified by combining the actual situation of lost circulation and fracture prediction results in field drilling (Fig. 9).
It is shown from Figure 9 that the well leakage has a good correspondence with the predicted fracture distribution. The fracture density of Ning 216 well area is obviously higher than that of Ning 201 and 209 well area, and the fracture distribution is complex. Correspondingly, the number of lost circulations of Ning 216 well area is obviously higher than that of well Ning 201 and 209 well area. It can be seen that the different degree of fracture development is one of the important reasons for the uneven horizontal distribution of lost circulation in Changning well area.

4.1.2. Relationship between in-situ stress field and lost circulation response. From the response diagram of stress and lost circulation in Changning block (Fig.10), it can be seen that the prediction results of the stress field have a good response to the actual lost circulation situation, and the leakage times in the high stress parts are less than those of the low stress. In the high part of the structure, the strata are buried shallowly, the in-situ stress is low, and the threshold pressure of fracture opening, extension and wellbore fracture is low, resulting in frequent lost circulation. On the contrary, the formation in the low part of the structure is deeply buried, the in-situ stress is large, the threshold of fracture opening, extension and wellbore fracture pressure is high, and the lost circulation is difficult to occur, so the number of lost circulations in the low part of the structure is less. It can be seen that the distribution of in-situ stress field in Changning block is also closely related to lost circulation.

4.1.3. Relationship between formation pressure and lost circulation response. The formation pressure and the flow resistance of drilling fluid must be overcome when the lost circulation occurs in natural fractures and karst caves. Therefore, for the drilling fluid with the same formation and drilling fluid formulation, the loss pressure is related to the formation pressure. The loss pressure is high where the formation pressure is high, and it is difficult for the lost circulation to occur. On the contrary, it is relatively easy for the lost circulation to occur. The relationship between formation pressure and lost circulation response is shown in the figure 11. According to the response diagram of formation pressure and lost circulation, it can be seen that the formation pressure of Ning 216 well area with frequent lost circulation, such as Ning 216H6 platform, is low; Ning 209 well area with less lost circulation, such as well H10-8 in Ning 209 well area, is located at a higher formation pressure. It can be seen that the distribution of formation pressure in Changning well block is also one of the key factors leading to lost circulation.

4.2. Verification of influencing factors of vertical distribution difference of lost circulation
There are obvious vertical differences in the distribution of formation geological and lithologic characteristics, in-situ stress, formation pressure and fracture development in Changning block, and the types and influencing factors of lost circulation in oil drilling are different. The following comparative analysis of the vertical distribution of formation lithologic characteristics, in-situ stress and formation pressure in Changning block is shown in figure 12. In figure 12, the data curves of in-situ stress, formation pressure and formation lithology are shown on the left, the well structure is shown in the middle, and the main causes of well leakage in different well sections are shown on the right. It can be seen from the figure that the in-situ stress of well Ning 209 increases steadily with the increase of well depth. The shallow formation is mainly continental sand mudstone formation, the
formation pressure is a normal pressure system, the safety density window of drilling fluid is large, and the lost circulation channel is mainly returnable leakage caused by large formation fractures and karst caves, which is complex differential pressure lost circulation; The formation lithology in the middle is mainly continental carbonate rock, with open fractures developed. The formation pressure increases to about 1.3, the safety density window of drilling fluid narrows, the lost circulation channel is mainly open fractures with a certain opening, and the type of lost circulation is differential pressure lost circulation; The deep formation is mainly marine mud shale formation, the formation pressure gradient is generally about 1.65, the safety density window of drilling fluid is narrowed, the lost circulation channel is closed fracture, and the effective liquid column pressure at the bottom of the well is high, which leads to the opening and extension of closed fracture and induces lost circulation.

5. Conclusion

(1) The problem of lost circulation in deep shale in Changning well area is prominent, and its vertical and horizontal distribution is wide, and its regularity is not clear. Regional fracture development, in-situ stress field and formation pressure have obvious influence on lost circulation. The frequent occurrence of lost circulation in Changning block has high response to many factors such as fracture, in-situ stress field and formation pore pressure.

(2) Large open fracture leakage is related to fracture development and formation pressure. In the low structural part of Changning well block, the formation is deeply buried, the fractures are not developed, the formation pressure is high, the frequency of lost circulation is low and the critical pressure of lost circulation is high; In the high part of block structure, the formation is shallow buried, faults and large fractures are developed, the formation pressure is low, the lost circulation is serious and the critical pressure of lost circulation is low.

(3) The leakage of closed fracture and induced fracture is related to in-situ stress. In the syncline structure of Changning block, the strata are deeply buried, the compressive stress is strong, the minimum horizontal principal stress is high, the closed fracture extension and induced fracture are difficult, the lost circulation is not prominent, and the critical pressure of lost circulation is high; In the anticline structure, the strata are shallow buried, the compressive stress is weak, the closed fractures
are easy to extend, the induced fractures are easy to form under the external stress field, and the lost circulation is serious.

(4) The lost circulation in Chagnning well area is affected by formation lithology, structural characteristics, formation pressure and other factors, showing vertical distribution differences. The causes of shallow lost circulation in Chagnning well area is mainly the loss of return caused by large formation fractures and karst caves, the causes of lost circulation in the middle of the formation are mostly open fractures, and the causes of deep lost circulation are mostly formation closed crack opening and induced fractures caused by improper use of drilling fluid density.

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