The detection and distribution of formation pressure with Fan simple method in Yingxiongling Area

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Abstract: In the Yingxiongling Area of Qaidam Basin, the formation pressure system is complicated in vertical, and the high pressure mechanism has not been made clear, which has brought a great challenge to the drilling work. To solve this problem, in this study, an advanced method with acoustic velocity-density crossplot has been used to analyze the abnormal formation pressure in the Yingxiongling Area of the Qaidam Basin. The results have shown that the abnormal high pressure in the Yingxiongling Area is mainly caused by the under-compaction, and is mainly concentrated in the layers form N22 to E32. According to the pressure mechanism, the Eaton method and the Fan simple method have been selected to calculate the formation pressure in the typical high-pressure wells in the Yingxiongling Area of Qaidam Basin. By comparing with the formation pressure control data, it has been found that the Fan simple method is more consistent with the actual situations and the accuracy is higher. With the Fan simple method, the vertical and lateral distribution of the formation pressure in the Yingxiongling Area have been obtained. The pressure distribution is consistent with the actual drilling conditions, which provides good guidance and reference for the smooth drilling of the Yingxiongling Area. The application results indicate that this method has a good prospect for promotion and application, laying a good foundation for next work.

Keywords: Detection of formation pressure; abnormal high pressure; abnormal high pressure formation mechanism; Fan simple method; Yingxiongling Area.

1. Introduction
In the Yingxiongling Area, the formation pressure system is very complex in vertical, the distribution of high pressure and leakage is unclear, and unpredictability is high during drilling, accidents and complex situations such as lost circulation and overflow are prone to occur. Therefore, it is necessary to deepen the understanding of the formation mechanism of abnormal high pressure in the formation, to optimize the detection model of formation pressure to reveal the formation pressure distribution regularity in order to provide technical support for safe and rapid drilling in the area.

Formation pore pressure is a very important parameter in drilling planning, which is related to the safety and efficiency of drilling process, and is an important basis to determine the drilling fluid density window. According to the sequence of drilling operations, the evaluation methods on formation pore
pressure are usually divided into three categories, including pre-drilling prediction, monitoring while drilling and post drilling detection[1]. Currently, the detection of formation pressure methods used in China and abroad mainly include Eaton method, Fan simple method, Bowers method, Fan comprehensive interpretation method, etc. Among these methods, Eaton and Fan simple method are suitable for the calculation of formation pressure of mudstone formation and formation pressure of under-compacted origin; Bowers method is applicable to the calculation of formation pressure of mudstone formation and formation pressure of under-compacted and fluid expansion origin; Fan comprehensive interpretation method is suitable for calculation of the formation pressure of sand shale formation and formation pressure of the composite origin. However, calculation with these methods, the requirement for calculation data are high and the calculation is very complex.

2. Formation mechanism and identification of abnormal formation high pressure

2.1. Formation mechanism of abnormal high pressure

The formation of abnormal high pressure requires two prerequisites: ① A certain volume of pore space and pore fluid; ② A closed environment for storing high pressure fluid. The essence of overpressure formation is that the volume of fluid is larger than the volume of pore space, which occurs in three cases: ①The amount of pore fluid increases, and new fluid is added to the original fluid; ②The volume of pore fluid expands; ③The volume of the pore space is compressed[7].

According to the relationship between the overburden pressure, vertical effective stress and pore pressure of fine clastics, chilingar et al. (2004) divided the formation mechanism of abnormal high pressure into three categories, including the change of formation pore volume, the increase of pore fluid volume, and the movement of fluid. The change of pore volume may result in vertical load (under-compaction), lateral structural load (tectonism) and secondary cementation that lead to high pressure formation mechanisms. The increase of pore fluid volume may lead to high pressure formation mechanism of hydrothermal expansion, mineral transformation, hydrocarbon generation and thermal cracking, and fluid migration. The high pressure formation mechanisms of abnormal high pressure caused by the change of fluid pressure and fluid movement can be divided into five types, including osmosis, fluid pressure head, oil well production operations, permafrost environment, and relative density difference[8].

Ward et al. (1994), from the perspective of stress-strain (loading and unloading) during the deposition and compaction process, divided the formation mechanisms of abnormal high pressure into several situations, including the situation that accord with the original deposition loading curve, situation that accord with the unloading curve, and situation where porosity basically unchanged[9]. Thereafter, on the basis of Ward's theory, Fan Honghai et al. divided the formation mechanism of abnormal high pressure into four categories: 1) The situation that accord with the original sedimentary loading mechanism; 2) The situation that accord with the reloading mechanism; 3) The situation that accord with the unloading mechanism; 4) The situation that accord with the mechanism in which the porosity is basically unchanged[10]. Based on this classification method, the formation mechanism of abnormal high pressure can be further qualitatively determined by the crossplot of acoustic velocity-density of mudstone[11].

2.2. Determination of formation mechanism of abnormal high pressure

By plotting the acoustic velocity-density crossplot, the mechanism of the abnormal high pressure can be further determined. Specifically, the acoustic wave and density data of mudstone which deviate from the normal trend line in logging curve are extracted, and the acoustic velocity-density crossplot of mudstone section is drawn with density as abscissa and acoustic velocity as ordinate, which is compared with the trend line regressed from the acoustic velocity data of normal compaction section.

As shown in Fig. 1 (a), the scattered points of acoustic velocity density are mainly concentrated near the low value of the normal compaction trend line in the depth range, indicating that the mechanism of abnormal high pressure is under-compaction (loading process);
As shown in Fig. 1 (b), within the depth range, the acoustic density-velocity scatter is mainly concentrated right below the normal compaction trend section or slightly to the left, and deviates to the unloading curve with low acoustic velocity, indicating that the formation mechanism of abnormal high pressure is fluid expansion (unloading process);

As shown in Fig. 1 (c), the scattered points of acoustic velocity-density are mainly concentrated in the high value area of acoustic velocity right above the normal compaction trend section, which indicates that the formation mechanism of abnormal high pressure is tectonic compression (reloading).

2.3. Determination of formation mechanism of abnormal high pressure in Yingxiongling Area
Based on the analysis of the logging data of the interval transit time from a typical high pressure well in Yingxiongling Area, we can judge the horizon where the abnormal high pressure occurs. As shown in Fig. 2, in the logging curve of the interval transit time, a relatively large deflection occurred around 3600m, indicating an abnormal high pressure in this section of the well.

Then the formation mechanism of abnormal high pressure is determined by using acoustic velocity-density crossplot of shale. Firstly, establish the acoustic velocity and density data loading curve of the normal compaction section in the high-pressure well, and then plot the abnormal pressure section data in the crossplot. Observe the location of the data points, and then determine the formation mechanism of the abnormal high pressure in the high pressure well. The crossplot for this typical high pressure well is plotted as shown in Fig. 3. It can be seen that the 1000m-3600m well section is normally compacted shale, and the loading curve of normal compaction can be established based on it. The red points of the
well depth of 3600m-5200m are near the loading curve, which is in line with the characteristics of the mechanism of under-compaction.

![Acoustic velocity-density crossplot of mudstone](image)

**Fig. 3** Acoustic velocity-density crossplot of a typical high-pressure well in the Yingxiongling Area

The crossplot of acoustic wave and density of mudstone in three wells in Yingyingling Area is shown in Fig. 4. The high pressure in these three wells is formed due to the mechanism of undercompaction. The abnormal high pressure in Yingxiongling Area is caused by mechanism of undercompaction.

![Acoustic velocity-density crossplot in Well Shi 49-1, Well Shi 56 and Well Shi 52-1](image)

**Fig. 4** Acoustic velocity- density crossplot in Well Shi 49-1, Well Shi 56 and Well Shi 52-1
3. Fan simple method for detection of formation pressure

3.1. The establishment of model for Fan simple calculation

\[ V = a + bP_{ev} - ce^{-dP_{ev}} \]  

(1)

On the basis of the two-parameter empirical model proposed by Bowers in 2005, which is used to describe the relationship between acoustic velocity and vertical effective stress in the original sediment loading process, Fan Honghai et al. developed a function relationship between acoustic velocity and vertical effective stress, which is more suitable for deep muddy sediments. This function relationship takes the form of an empirical model of linear and exponential combination as below[4]:

Where: \( V \) is the velocity of sound wave; \( P_{ev} \) is the vertical effective stress; \( a, b, c \) and \( d \) are empirical coefficients.

3.2. Determination of model parameters for Fan simple method

When calculation with the Fan simple method mentioned above, it is necessary to determine the model parameters \( a, b, c \) and \( d \).

For a certain area, the model coefficients \( a, b, c \) and \( d \) should be constant. There are generally two methods to determine them on site.

According to the vertical effective stress data calculated by acoustic velocity and hydrostatic pressure of mudstone in normal compaction section, the above parameters are obtained by regression. Specifically, one or more drilled wells with good acoustic logging data should be selected in the study area where the formation changes little in the lateral direction, and the interval transit time of the mudstone section in the normal compaction section should be calculated by a certain algorithm and converted into velocity, and then the corresponding vertical effective stress can be obtained from the overlying formation pressure and hydrostatic pressure, and then the acoustic wave velocity and vertical effective stress are regressed to obtain the parameter values of \( a, b, c, d \).

The above parameters can be obtained by regression using the measured formation pressure data and the corresponding acoustic logging data. Equation 2-1 is a non-linear regression equation, which is relatively complicated. Therefore, the stepwise forward regression method can be adopted, that is, one \( d \) is fixed each time, and \( a, b, c \) can obtained by regression, and their variances shall be recorded (generally varying from 1 to 40). After all regression is completed, the minimum values of \( a, b, c, d \) of variance are determined as the final results.

After the above equation is obtained by regression, the functional relationship between acoustic velocity and vertical effective stress can be obtained. According to the vertical effective stress theorem, combined with the overlying formation pressure data, the value of formation pressure can be calculated [4].

4. Optimization of detection of formation pressure model

According to the pressure mechanism, Eaton method and Fan simple method are selected to calculate the formation pressure of typical high pressure wells in Yingxiongling Area, Qaidam Basin, as shown in Fig.5.
With the above two methods, the high pressure at the typical high-pressure well section were detected in the Yingxiongling Area. Among the two methods, the highest pressure detected by Eaton method was 2.1 g/cm$^3$, and the highest pressure detected by Fan simple method was about 2.25 g/cm$^3$. According to the well history, the highest pressure here should be range from 2.2 g/cm$^3$ to 2.3 g/cm$^3$. The comparison results show that the pressure detection accuracy by Fan simple method is higher. Moreover, the Fan simple method is suitable for the calculation of formation pressure in mudstone formation and under compaction mechanism. Therefore, in this study, the Fan simple method is selected as the model for detection of formation pressure in Yingxiongling Area.

On the basis of the existing logging data, the model parameters for the detection of formation pressure are fitted, and the calculation model is obtained as follows:

$$V_P = 4.0741 + 10.720P_e - 2.658e^{-15.89P_e}$$

5. **Vertical and lateral distribution of formation pressure in Yingxiongling Area**

5.1. **Vertical pressure distribution of regional formation**

The vertical profiles of formation pressure in Well Shi 41H2, Well 52-1 and Well Chai 10 in Yingxiongling Area were obtained through calculation with this equation, as shown in Fig. 6. The vertical distribution of formation pressure in the whole area is shown in Fig. 7.
Vertically, the distribution characteristics of formation pressure are as follows: first, the pressure changes very rapidly in the vertical direction, sometimes there is a sudden sharp increase, which has a great impact on drilling; second, the formation pressure generally rises rapidly after reaching the depth of 4000m, reaching the formation pressure of 2.0 g/cm$^3$; Third, when the depth reaches about 5000m, the formation pressure is basically greater than 2.0 g/cm$^3$, and the local high pressure can even reach about 2.25 g/cm$^3$.

5.2. Lateral pressure distribution of regional formation
To further understand the lateral distribution of formation pressure in Yingxiongling Area, the data of inter-salt and sub-salt formation pressure in some wells are collected, and the lateral formation pressure
distribution of N1 formation and the five formations of E\textsubscript{32} in Yingxiongling Area was obtained through calculation, as shown in Fig. 8.

![Fig. 8 Lateral distribution of formation pressure in N1 and E\textsubscript{32} I, E\textsubscript{32} II, E\textsubscript{32} III, E\textsubscript{32} IV and E\textsubscript{32} V formations](image)

It is not difficult to see from the lateral distribution map of formation pressure in Yingxiongling Area that the formation pressure of N1 formation in Ganchaigou Well Block is equivalent to that of Yingzhong No.1 structure and No.2 structure, showing a trend of high in the north and south and low in the middle. The pressure of the E\textsubscript{32}I formation gradually decreases from Yingzhong No. 3 structure to northwest Yingzhong belt, and the pressure drop gradient is large; the formation pressure of the E\textsubscript{32} II formation gradually decreases from the Yingzhong No. 3 structure to the Yingzhong No. 1 structure, and the formation pressure is relatively high in the Ganchaigou Well Block and the Yingzhong Area, and the lowest in the Yingxi middle and southern belts. The formation pressure of E\textsubscript{32} III formation shows a trend of high in the south and low in the north, and the pressure drop gradient is relatively gentle. The overall formation pressure in the Yingzhong Area of E\textsubscript{32} IV formation is very high, and the pressure in the Ganchaigou Well Block is basically the same as that in the Yingxi middle belt, and the pressure in other areas is relatively low. The formation pressure of E\textsubscript{32} V formation gradually decreases from Yingzhong to Yingxi and Ganchaigou, and the pressure in north belt of Yingxi well block is the lowest. There is a widespread high pressure distribution in the southern Yingzhong area of the entire region.
From the E22II formation, the formation pressure gradually increases to the north, west, and northwest with the increase in depth, starting to be higher than the normal hydrostatic pressure. Understanding the horizontal macroscopic distribution of formation pressure is beneficial to provide good guidance for subsequent drilling operations in this area.

6. Conclusions
In view of the complicated system of vertical formation pressure and unclear formation mechanism of high pressure in Yingxiongling Area of Qaidam Basin, we have conducted analysis about the abnormal formation pressure mechanism in Yingxiongling Area by using acoustic velocity-density crossplot method. The results show that the abnormal high pressure in Yingxiongling Area is mainly caused by undercompaction. Furthermore, according to the formation mechanism of high pressure, Eaton method and Fan simple method have been selected to calculate the formation pressure of typical high pressure wells in Yingxiongling Area, Qaidam Basin. By comparing with the formation pressure control data, it has been found that the Fan simple method is more consistent with the actual situation and the accuracy is higher. With Fan simple method, the vertical and lateral distribution of formation pressure in Yingxiongling Area have been obtained. It has been found that the abnormal high pressure zones are mainly concentrated in N2 to E3 layers. The pressure distribution is consistent with the actual drilling conditions, which provides good guidance and reference for the smooth drilling of the Yingxiongling Area. The application results indicate that this method has a good prospect for promotion and application, laying a good foundation for the next step.

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