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Pressure Prediction for High-Temperature and High-Pressure Formation and Its Application to Drilling in the Northern South China Sea

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Abstract There are plentiful potential hydrocarbon resources in the Yinggehai and Qiongdongnan basins in the northern South China Sea. However, the special petrol-geological condition with high formation temperature and pressure greatly blocked hydrocarbon exploration. The conventional means of drills, including methods in the prediction and monitoring of underground strata pressure, can no longer meet the requirements in this area. The China National Offshore Oil Corporation has allocated one well with a designed depth of 3200 m and pressure coefficient of 2.3 in the Yinggehai Basin (called test well in the paper) in order to find gas reservoirs in middle-deep section in the Miocene Huangliu and Meishan formations at the depth below 3000 m. Therefore, combined with the '863' national high-tech project, the authors analyzed the distribution of overpressure in the Yinggehai and Qiongdongnan basins, and set up a series of key technologies and methods to predict and monitor formation pressure, and then apply the results to pressure prediction of the test well. Because of the exact pressure prediction before and during drilling, associated procedure design of casing and their allocation in test well has been ensured to be more rational. This well is successfully drilled to the depth of 3485 m (nearly 300 m deeper than the designed depth) under the formation pressure about 2.3 SG (EMW), which indicate that a new step in the technology of drilling in higher temperature and pressure has been reached in the China National Offshore Oil Corporation.

Key words: formation pressure, high temperature, overpressure, pressure prediction, Yinggehai Basin, South China Sea

1 Introduction

In general, the burial depth of the top of overpressure systems in the Yinggehai Basin is at a depth about 3000 m. However, the local overpressure systems have obviously changed because of the disruption of transferred overpressure through faults and diapir. For example, an overpressure compartment has been encountered at very shallow strata of some structural zones, which is due to the good connection of shallow reservoirs with deep overpressure systems by faults in diapir. The minimum depth to encounter abnormally pressured system is at the depth of 1450 m. Unlike conventional overpressure systems, this kind of transferred overpressure systems do not have an uncompaction phenomena in the log curve (Xie et al., 2003). So, it is difficult to predict it. In this study, we dealt with the mechanism and distribution of overpressure systems, and then set up the geological model of the formation pressure that is fit for the Yinggehai Basin in order to predict exactly the formation pressure.

The method for prediction of pressure before drilling is mainly based on seismic velocity, because of small number of wells drilled on the offshore area. In the central diapir zones of the Yinggehai Basin, lots of faults developed, strong hot fluid flow from the deep and result in the occurrence of plentiful gas in the shallow beds. Seismic images become blurred in gas-bearing traps because of the presence of gas, and at the same time seismic velocity is also affected greatly. Hence, detailed analysis of seismic velocity is the basic work to predict accurately the formation pressure, and it is important to find a technology and method that can either increase resolution or ensure the information of velocity with existing seismic data.

Because of the limitation of precision of interval velocity calculated by seismic data and complication of geological background, such as in allochthonous overpressure systems, it is inevitable that there are error in predicting formation pressures before drilling. So, we detect and correct the formation pressure by routine wire-line logs in the course of drilling to monitor and correct the predicted result. In order to get the formation pressure in real time, especially in the transitional area where the pressure increases rapidly, so the upward traveling wave of VSP (vertical seismic profiles) and SWD (seismic while drilling) are also used to get the exact velocity and predict the distribution of the formation pressure ahead of the drilling bit.

In addition, on the basis of the methods of monitoring the formation pressure by routine drilling and logs, we developed a method of integrated rock intension and rock mechanics parameter (Gao, 1999) in consideration of the mechanism of allochthonous overpressure systems. This method combined with multiple methods of monitoring the formation pressure offered by the ALS-2 software can be used to predict more accurately the formation pressure.

On account of the limitation of seismic, logs and drilling information, application of any one method does usually not meet the demand of drilling, so, we attempt to synthesize all of the available data. In the course of drilling, according to comparison and correction of research results by multiple methods in predicting or monitoring processes, an integrated method to predict circularly the formation pressure and improve progressively the precision of prediction has been pointed out on the basis of the characteristics of pressure prediction and monitoring in each segment.

2 Pore Pressure Predictions before Drilling

2.1 Refined processing of seismic velocity

It is important in the formation pressure prediction before drilling to obtain seismic velocity as exactly as possible. The test well is located in the blurry zones in a diapiric structure where there are lots of multiple waves so that the seismic images processed by routine method do not show clearly. So, the defined processing of the seismic data has to be done to suppress multiple waves and enhance signal-noise ratio. Therefore, before drilling, a new method including the *F-K*, τ-*P* domain filtering has been used to process carefully the seismic profiles in this diapir structure zone to improve seismic velocity precision. In order to avoid error caused by local factors of pressure prediction at one point, reliable seismic velocity profiles and predictive formation pressure coefficient profiles have been achieved by the MVA technology. On the basis of that, the above velocity charts of the profiles that traverse wells are interpreted carefully, and further the vertical changes of formation pressure in the test well are predicted. In the velocity charts processed finely by different methods, the multiple waves are obviously suppressed, while the exact velocity in overpressure transition zones is distinctly picked up.

2.2 Geological models of pressure prediction

Three pressure prediction models have been used in this research to predict formation pressure before drilling to further analyze pressure structure in overpressure transition zones.

There are relative stable distributions of sedimentary facies in the interval between T30 and T40 (Upper Miocene) in this area. Delta sandstone developing on T31 surface is located in the lower part of overpressure transition zones (Gong et al., 1997). The compaction logs, real pressure and core slice observation of adjacent wells indicated that the transition zones are also characterized by delta deposition, therefore it can be used to instruct pressure prediction of the test well.

By analyzing the pressure distribution in the profiles that traverse test well and its adjacent wells, it can be inferred that the overpressure system (The pressure coefficient is 2.05) measured in one adjacent well appears 300–400 m above the top surface of background overpressure, so, it is an allochthonous overpressure. On the other hand, the measured pressure also shows that the pressure distribution in overpressure transition zones is affected by faults. Sandstone beds are subdivided into several pressure systems. By synthetic modeling of several pressure prediction models, and demarcation of the real measured pressure of adjacent wells on the basis of velocity charts which have been finely processed, it can be found that abnormal pressure zones can be divided into background pressure and transition zones, and in the latter the pressure is characterized by stair stepping distribution because of local connection of faults.

In this study, the pressure model is based on normal compaction (Model I), the EATON method is applied to mudstone pressure prediction. While in the transition zone and overpressure zone, two allochthonous overpressure model caused by faults, Model II and Model III, are applied to pressure prediction. The initial pressure in Model II and Model III is fracturing pressure of strata, the opening time of fault is at 0.025 Ma, and in model III, and the faults are not closed basically.

2.3 Results of synthetic pressure prediction

The prediction results of the above methods show that the test well will get into the transition zones at about 2310 m, and the pressure coefficient will got up to 1.45, while the overpressure beds will occur at the depth of 2686 m, the pressure coefficient will be more than 2.0. Hence, we suggest that two casings should be run respectively at the depths of about 2250 m and 2600 m to ensure the safety of drilling.

3 Pressure Monitoring and Prediction Correction in the Course of Drilling

The goal of monitoring the formation pressure while drilling is to understand the pressure situation of drilled strata at any time, which can be used to correct the prediction results before drilling so that safety measures of drilling can be adopt in time.

Based on the result of pressure prediction that indicated the test well would drill into the strong overpressure formation at the depth of 2686 m, the designed depth of casing with a diameter of 244.5 mm was going to run at the depth of 2598 m in consideration of safety. In addition, the casings with a diameter of 339.7 mm were also run at a shallower depth. At the location of the test well, the distribution of overpressure is complicated and fractured pressure is very closed to the formation pressure. Clearly, it is important to ensure the point to stop drilling and run casings at the depth of 8–10 m into shale strata above the top of overpressure zones during drilling in the segment. Hence, the frequency of monitoring would be increased after getting into overpressure zones, and all drilling, log and seismic information while drilling and VSP would be applied to prediction so that the premonition of overpressure could be found as early as possible.

In the whole course of drilling of the test well, our methods were applied to monitoring the formation pressure with time, and the special parameter and empirical coefficient were obtained. On the basis of substantive statistics and data of other wells in the same structure zones, the slope of the trend line of the *Dc* index is 0.002820.

In order to ensure the accuracy of monitoring, except for the method of the *Dc* index, lots of other methods have been used to monitor formation pressure, which include mud log, drilling rate, balance between slurry and pore pressure, surface height of the slurry pool, density of returned slurry and the flux at the exit.

As a result, the normal-pressure systems occur at the depth of 0–2077 m in the test well. So, we advised to change the original drilling design and allowed the casings with a diameter of 339.7 mm to be run 100 m deeper into the pure mudstones below the sandstones in the Huangliu Formation. It enhances the formation's capability to bear pressure and decreases the difficulty for posterior drilling. Moreover, the casings with a diameter of 244.5 mm are also allocated to set down at the depth that is 100 m deeper than the designed one. It is that the two casings are set down at the appropriate place, which ensures the safety of drilling although the drilling depth of the test drill is 300 m deeper than the designed drilling depth.

4 Pressure Prediction during Drilling

For pressure prediction during drilling, three methods have been used in this study, i.e. middle VSP inversion, SWD inversion and neural net of middle logs.

4.1 Pressure prediction during drilling inversed by middle VSP

The application of the inversion of the middle VSP is one of the important methods for predicting pressure while drilling. In order to predict accurately the formation pressure, two middle VSP jobs were done when the test hole was drilled to the depths of 2100 m and 2510 m. Through the separation of upward and downward traveling waves, inversed wave impedance, conversion of the Gardner coefficient and proper restriction of the trend line of low frequency, the interval velocity has been obtained. With this method, the interval velocity of the strata can be accurately predicted at the depth of 200–500 m ahead of the drilling bit. The results indicate that the sharp variation of abnormal pressure occurs respectively at the depths of 2300 m and 2700 m.

4.2 Pressure prediction while drilling inversed by SWD

The method of SWD is applied to the test well, which is used first in the Chinese National Offshore Oil Corporation. Through the inversion of upward traveling waves, with the method of SWD, the velocity of undrilled strata can be obtained about 200–500 m ahead of drilling bit in real time. It plays an important role in predicting two sharp surfaces of overpressure respectively at the depths of 2301 m and 2737 m. Before drilling to the second overpressure surface (predicted at 2686 m), results of SWD show that the pressure coefficient is up to 1.80 at the depth of 2605 m and it is larger than 2.00 at the depth of 2730 m. Those results have been proved by the further measurement.

4.3 Pressure prediction while drilling by neural net of middle logs

On the site of detecting and monitoring at the test well, the method of neural net has been applied to analyzing in middle logs to predict formation pressure while drilling. Firstly, the velocity eigenvalues are calculated by seismic parameters, which are picked up from pass tracks in the seismic profiles traversing the well. And then, a neural net model has been set up. Finally, after comparison with real measurement in the well and precision analysis, the model is applied to predicting acoustic velocity at the depth of 300 m ahead of drilling bit. In the course of the whole drilling, this model is adjusted five times by the middle VSP, which can be used in predicting pressure coefficient in the pressure transition zone, and top surface of overpressure.

5 Accuracy Analyses and Discussion

This study is done during the drilling process, and theoreticalresearches, method experiments and applications of results are going along while drilling. The precision of pressure prediction, measurement and monitoring during drilling is relatively high. The error of predicted overpressure surface and pressure values is small, which provides important parameters for the test well to drill successfully. The real drilling results show that the top of the first overpressure variation surface is at the depth of 2301 m, which has a 9-m difference from the predicted depth of 2310 m and its relative error is 0.39%. The top of the second overpressure variation surface is at the depth of 2737 m, which has a 51-m error from the predicted depth of 2686 m and the relative error is 1.86%. The error range of predicted pore pressure coefficient is between .3.25% and 8.0%, and the error range of the predicted overpressure surface depth is between .1.86% and 0.39%.

It is proved by the real drilling that it is effective to predict pressure by lots of data with drilling, especially to confirm the top depth of overpressure variation surface and the depth of casings, which adjusts the predicted results before drilling again and again and make the error smaller to meet the engineering demand. The relative error of predicting the top depth of overpressure variation surface with drilling is from–1.00% to 0.40%. The predicted top depth of overpressure variation surface is at the depth of 2700 m and the predicted pressure coefficient is 1.82, and the real depth is proved at the depth of 2738 m, which is only 38 m deeper than the predicted one.

In one word, on the basis of foregone experiences and methods, through the integrated researches including geology, geophysics, logs and drilling, a series of methods of predicting formation pressure and monitoring with drilling are pointed out which is fit for clastic rocks in the Yinggehai and Qiongdongnan basins. Furthermore, the main results have been applied to instructing drilling at the higher temperature and overpressure condition, which reached a successful result for economic and social benefits.

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