Application of Fracture Distribution Prediction Model in Xihu Depression of East China Sea

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Abstract. There are different responses on each of logging data with the changes of formation characteristics and outliers caused by the existence of fractures. For this reason, the development of fractures in formation can be characterized by the fine analysis of logging curves. The well logs such as resistivity, sonic transit time, density, neutron porosity and gamma ray, which are classified as conventional well logs, are more sensitive to formation fractures. In view of traditional fracture prediction model, using the simple weighted average of different logging data to calculate the comprehensive fracture index, are more susceptible to subjective factors and exist a large deviation, a statistical method is introduced accordingly. Combining with responses of conventional logging data on the development of formation fracture, a prediction model based on membership function is established, and its essence is to analyse logging data with fuzzy mathematics theory. The fracture prediction results in a well formation in NX block of Xihu depression through two models are compared with that of imaging logging, which shows that the accuracy of fracture prediction model based on membership function is better than that of traditional model. Furthermore, the prediction results are highly consistent with imaging logs and can reflect the development of cracks much better. It can provide a reference for engineering practice.

1. Introduction

During the course of oil and gas drilling, fractures are often encountered in formation. Fracture can act as storage space and migration channel of oil and gas in formation, but it also can cause drilling fluid leakage, collapse of wellbore and other engineering problems [1]. Therefore, it is necessary to study the development degree and distribution laws of fracture in formation before drilling. The existing methods for formation fracture distribution evaluation mainly include field outcrop or laboratory core observation, conventional logging data analysis, imaging logging data interpretation, P-wave amplitude variation with offset (AVO) and amplitude variation with azimuth (AVA) monitoring, S-wave splitting monitoring, multi-band component monitoring, three-dimensional seismic inversion and other seismic prediction techniques, discrete fracture network (DFN) geological modelling, tectonic stress field numerical simulation and other methods [2, 3]. The above research methods have achieved some achievements in fracture prediction, but there are also many defects, such as high difficulty in underground core acquisition in fractured formation, high cost of imaging logs and limited coverage area, low resolution and multi-solution of seismic prediction results, drastic effects on geological modelling and numerical simulation by the actual geological data and model and so on. Thus, the formation fracture prediction method has yet to be further improved. In this study, a prediction model of fracture is established based on membership function by using statistical method.
with the NX tectonic drilling engineering data of Xihu depression in the East China Sea. By comparing and analysing the prediction results with traditional model and imaging logging, the membership function model is proved to be more accurate and perfect.

2. Logging response to fracture development

Different log methods have different responses to various features of formation, and the development of fractures in formation can cause some logging data to be abnormal. Therefore, to a certain extent, the development and distribution of formation fracture can be characterized by logging data. Among them, the log methods such as resistivity, sonic transit time, density, neutron porosity, gamma ray, density compensation, photoelectric absorption cross section index, electromagnetic wave, imaging, etc. are more sensitive to formation fracture [4, 5].

2.1 Resistivity logging

The resistivity of rocks is closely related to lithology, porosity and formation water properties. Therefore, some properties of formation rocks can be obtained by studying the resistivity logging data. For example, the formation characteristics will be converted with the changes of partial properties of original porous medium due to the invasion of fluid in borehole in fractured formation. Resistivity value is significantly reduced by drilling fluid intrusion around the hole in fractured formation, and which shows low value resistivity in the high resistivity background on logging curves. The resistivity logging curves are often undulate and rugged peak due to the non-homogeneous development of formation fracture and it also appears as a low value, in which the high angle fracture shows positive difference, while the horizontal fracture, bedding and dissolution holes show negative difference in fractured formation [6].

2.2 Acoustic logging

The sonic transit time logs are a logging method to estimate formation porosity and other properties by measuring the propagation time difference of slip wave through formation. When formation fracture develops, they absorb a large amount of acoustic energy, making sound waves decay considerably, and it shows a sharp change of amplitude in sonic transit time logging curves, which is called “cycle skip”. The sonic transit time logging is poor for high-angle fracture but the acoustic energy decays rapidly and there will be a significant frequency jump when encounters a large level of horizontal or reticular fractures [7, 8].

2.3 Density logging

$^{137}$Cs is usually used as gamma source in density logging. The scattering and absorption capacity of gamma photon varies with formation density, so that the gamma photon count rate received by the detector at different depths is different, which makes the results reflected in logging curves. There is a computational relationship between porosity, skeleton density, pore fluid density and rock mass density, so that when rock skeleton density and pore fluid density are known, the formation porosity (including the contribution of fracture) can be obtained by using the logging mass density. When formation fractures are developed, the scattering and absorption capacity of gamma photons is obviously enhanced, so that the gamma photon counting rate received by detectors can be greatly reduced [8]. Therefore, the density logging is generally showed a significant low value phenomenon in fractured zones.

2.4 Compensated Neutron logging

Compensated neutron logging is a log method to determine the formation porosity by detecting the thermal neutron density in formation. The deceleration effect on thermal neutrons varies with porosity due to the hydrogen contents in different formation, which makes the thermal neutron density near the radiation source different. The thermal neutron capture cross section of chlorine in the nuclides that make up the sedimentary rocks is the largest, so the formation chlorine content determines the trapping
properties of rocks. The spatial distribution of thermal neutrons is related to both the hydrogen content and the amount of chlorine of formation, that is, the magnitude of thermal neutron count is determined not only by the deceleration of formation but also by the trapping properties. Because of the high hydrogen and chlorine contents in fractured formation, the capture cross section is large and the deceleration length is small, which leads to a result that the number of thermal neutrons that can be detected near radioactive source is obviously increased. Therefore, the compensated neutron logging values have a significant increase in fractured formation [9].

2.5 Gamma ray logging
Gamma ray logging is a method that studies the formation properties by detecting the intensity of gamma rays in rock formation. When formation fractures are rich, some radioactive materials (such as uranium) are deposited in the opened fracture due to the increase of shale content or the circulation of groundwater, which will increase the radioactive material contents in formation. Gamma ray logging is usually used to detect and evaluate radioactive minerals, that is, the gamma logs show a significant high value in fractured formation. It can be used to detect the development of fracture in formation by the combination of gamma logs responding to fracture with other logging curves.

3. Two models for predicting fractures with well logging data
According to the study of Liliana P. Martinez et al. of the University of Oklahoma, a membership function prediction model of fracture distribution is established by using the statistical methods. And then, the vertical distribution laws of fractures are calculated by combining the data of conventional logs. That is to say, the variation laws of fracture index with well depth are calculated by using logging data [10, 11].

3.1 Normalization of logging data
In this study, the formation fracture index is calculated by using logging data such as sonic transit time, gamma ray, density, compensated neutron, and shallow or deep resistivity. In order to make the respective measurement have same dimension to eliminate the effect of larger or smaller data values, the original logging data must be normalized:

\[ Z_i = (X_i - a)(b - a)^{-1} \]  (3.1)

Where,
\( Z_i \) is logging data after normalized;
\( X_i \) is logging data before normalized, which usually takes the absolute value of the difference between the data points of each logging curve and the fitted trend line:
\( a \) and \( b \) are constants, which usually take the minimum and maximum value of logging data, respectively.

3.2 A traditional model for predicting fracture growth
It can be seen from the foregoing discussion that logging data such as sonic transit time, gamma ray, and density can be used to calculate and characterize the development of formation fracture index, but fractures are usually not the only factors that affect logging data. Formation lithology, comprehensive characteristics of drilling fluid, pore pressure, manual and other factors will also cause changes in logging data, resulting some abnormal data in logging curves. In order to consider these factors comprehensively and minimize their impact in the maximum extent, it is still necessary to average the single fracture index derived from each logging method to obtain the comprehensive fracture index, basing on the normalization of the original logging data [4]. The traditional prediction model of fracture development is shown below:

\[ N_i = \sum w_i Z_i \]  (3.2)

Where,
\( N_j \) is formation comprehensive fracture index predicted by traditional model;
\( Z_i \) is the normalized logging data or is called single fracture index;
\( w_j \) is weight coefficient corresponding to the single fracture index \( Z_i \), which can be obtained by inversion of the adjacent well data.

### 3.3 Prediction model for fracture development based on membership function

Although there is a certain relationship between the sonic transit time, gamma ray, spontaneous potential, density, compensated neutron, shallow and deep resistivity logging data, but the specific relationship in mathematics is not easy to describe, and the traditional model only uses simple weighted average to consider the deviation of each logging data, which will affect the prediction accuracy. Therefore, the fuzzy mathematical theory is used to relate these logging data to the development of formation fractures, and a prediction model based on membership function has established \(^{[12]}\). When using the original logging data, the traditional model requires subjective analysis and judgment of the overall trend line and abnormal data points, which is greatly affected by the subjective experience of the analyser. The key is to build the criterion of recognition judgment and determine certain attribution principles to establish the membership function model of standard type \(^{[13,14]}\) When the fuzzy mathematics theory method is used to identify the type of analysis object in the prediction model based on membership function. Based on the principle of maximum membership degree, the relationship between logging data and formation fracture index is established by fuzzy theory, and the membership function is as follows:

\[
\left[1 + \exp \left( -c(Z_i - d) \right) \right]^{-1} \tag{3.3}
\]

Where,
\( n_i \) is membership degree, or is called fracture index obtained by \( Z_i \);
\( c \) and \( d \) are constants, and which are determined by the relationship between logging data and fracture index. For different logging methods, the values are different and can be obtained by inversion of the adjacent well data.

The fracture index \( n_i \) corresponding to different logging methods can be obtained by membership function. In order to synthetically consider the influence of various factors on formation fracture index, the membership value \( n_i \) is weighted average, and then the fracture index can accurately reflect the probability of fracture development, that is to say, the formation with high fracture index indicates high probability of formation fracture development. In the case of comprehensive consideration of each logging method, the general fracture index is calculated as follows:

\[
N_2 = \sum w_i n_i \tag{3.4}
\]

Where,
\( N_2 \) is the stratigraphic comprehensive fracture index predicted by the membership function model;
\( n_i \) is the membership degree, or is called fracture index obtained by \( Z_i \);
\( w_i \) is the weight coefficient of membership \( n_i \), which can be obtained by inversion of the adjacent well data.

### 4. Application

The NX structure is located on the north of Xihu depression in East China Sea continental shelf basin, and the tectonic is an anticline formed in the background of the central reversal belt strike slip stress field, showing NE distribution and the whole structure shape is complete. From the vertical point of view, the faults are rich and the inclination is between 60° and 70°, which belong to high angle faults; From the horizontal point of view, a number of seismic reflection depth maps also show a certain number of fault development. Therefore, the formation fracture in the tectonic zone can be...
predicted and grasped by the method described above. The variation of fracture index with well depth was predicted by traditional model and the model based on membership function with conventional logging data such as sonic transit time, density, resistivity, neutron and gamma ray of well NX-Y-1, respectively, and was compared with the observed results of imaging logging, as shown in Fig. 1.

![Fig. 1. The comparison of two kinds of fracture index models with partial FMI of NX-Y-1](image)

Fig. 1 shows the comparison of imaging logging data with the results of two fracture index prediction models of three sections in NX-Y-1 well. It can be seen from Fig.1(a) and 1(b) that the tectonic fractures of the above two well sections are obviously developed, which is consistent with the prediction results of two fracture prediction models. Further comparison between Fig.1(a) and 1(b) shows that the predictive results of membership function model are more consistent with imaging logs in the case where both models predict fracture development. In the well section shown in Fig.1(c), the results of traditional model show that there is fracture in the local development but the membership function model shows that there is no obvious fracture development while the imaging logging shows there is no fracture development in Fig.1(c). Based on the above three sets of comparative analysis, the traditional model has some errors in the prediction results of formation fracture index, and it is not accurate to judge whether there are fractures in formation. The model of membership function is more reasonable to predict the development and distribution of formation fractures, which is consistent with the observation results of imaging logs basically.

5. Conclusions

1) Formation fracture will cause some logging data to produce abnormal response; therefore, we can study the formation fracture development degree and distribution laws by appropriate function prediction model with resistivity, sonic transit time, density, neutron, gamma ray and other logging data.

2) In order to establish prediction model of formation fracture index based on the membership function, a statistical method was introduced. It is characterized by the fuzzy mathematics theory to determine the type of analysis object in analysis process of logging data, thus avoiding subjective factors of the analysers and making prediction results are more accurate and reasonable. The membership function model of fracture index is used to predict the longitudinal distribution of fracture index with well depth, and then the development of formation fracture is analysed.

3) Based on the comparison of prediction results of fracture development in a certain well in NX structure of Xihu depression, it is shown that the analysis result based on membership function is consistent with the observation results of well logs and the prediction accuracy is superior to the traditional model, which can provide a better reference for drilling engineering and development practice.
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