5.6 GAS-WATER DETECTION TECHNOLOGY AND APPLICATION OF LOTEM COMBINED WITH WELL LOGGING AND SEISMIC DATA

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ABSTRACT

Accurate detection of gas-water front and oil-water boundary is crucial for efficient development of oil and gas fields. The comprehensive geophysical technology of fully integrating seismic methods with high spatial resolution in fluid identification and electromagnetic methods with high sensitivity to reservoir fluids is currently a major research topic in oil and gas field development. This paper is based on the multi-component LOTEM observation data of the Feixianguan Formation reservoir in the main structural area of Puguang Gas Field. Through the static shift correction and the joint inversion of electrical and magnetic components under well seismic constraints, the resolution of resistivity and polarizability inversion is improved. A method for defining the gas-water identification factor Q based on linear coupling of multiple sensitive parameters, using resistivity and polarization as sensitive parameters, combined with seismic attribute parameters Vp/Vs, phase, and formation dip angle, was proposed. A Q-value gas-water identification template was established through the calibration with logging interpretation data and water invasion parameters of production gas wells. The gas-bearing properties of the I-VI sequences in the Feixianguan reservoir of the Puguang gas field experimental area were explained, The correctness of its interpretation results was verified by P103-2C lateral drilling. The test shows that the gas-water detection technology integrated by seismic and LOTEM has the ability to detect deep gas-bearing degree, and can be an important technical means for unconventional oil and gas development gas-water detection.

KEY WORDS: LOTEM, Gas-Water detection, resistivity, polarizability, water invasion.

INTRODUCTION

The gas-water detection is a research hotspot in the exploration and development of unconventional oil and gas, and it is also a global challenge. Currently, in the mid-to-late stage of unconventional gas reservoir development, water flooding is a serious issue in China, posing significant challenges to the sustainable development. Seismic method has strong detection capabilities and high resolution, making it the primary means of gas and water detection. However, the application effectiveness is seriously affected by the poor acoustic properties of unconventional oil and gas reservoirs. Meanwhile, the analysis of electrical testing for the unconventional reservoir rocks indicates that resistivity and polarization are remarkably sensitive to reservoir fluids. Compared to the seismic method, electromagnetic (EM) method has the physical advantages in the identification of gas and water in unconventional reservoirs. To achieve the identification of gas and water in deep and ultra-deep conditions (with depths greater than 5000 meters) by EM method, we should focus on the accurate extraction method of the EM parameters and the modeling of the relationship between the EM parameters and gas-water

content. And we also should make full use of the benefits from seismic and EM methods, and finally develop a multi-parameter joint identification technique for gas and water using seismic and EM data.

METHOD and APPLICATION

Based on the Long Offset Transient Electromagnetic Method(LOTEM) multi-component data, we achieve the resolution capability improvement for the electrical resistivity and polarization inversion, by using the magnetic component to correct the static shift of the electric component and employing well-constrained joint inversion of the electric and magnetic components. We define the gas-water identification factor Q based on the linear coupling of the main sensitive parameters, including electrical resistivity, polarization, seismic attribute parameters (Vp/Vs ratio, phase, and formation dip angle). The calculation formula is as follows:

Q =$\boldsymbol{a}$1$\boldsymbol{R}$+$\boldsymbol{a}$2M+ $\boldsymbol{a}$3Vp/Vs+$\boldsymbol{a}$4Imp+ $\boldsymbol{a}$5D

where $\boldsymbol{R}$ represents the normalized electrical resistivity, $\boldsymbol{M}$ represents the normalized polarization rate, Vp/Vs is the normalized P-wave to S-wave velocity ratio, Imp is the normalized impedance, $\boldsymbol{D}$ is the normalized formation dip angle, $\boldsymbol{a}$1、$\boldsymbol{a}$2、$\boldsymbol{a}$3、$\boldsymbol{a}$4、$\boldsymbol{a}$5 are the weighting coefficients for the sensitive parameters. $\boldsymbol{a}$1+$\boldsymbol{a}$2+$\boldsymbol{a}$3+$\boldsymbol{a}$4+$\boldsymbol{a}$5=100%. $\boldsymbol{a}$1 and $\boldsymbol{a}$2 have values between 30% and 55%, while $\boldsymbol{a}$3, $\boldsymbol{a}$4, and $\boldsymbol{a}$5 have values between 10% and 25%. Commonly, the gas-water interpretation results from multiple wells and the specific calculations of the gas-water identification factor (Q) are compared to determine the weighting coefficients that best match the well logging interpretation results. This establishes a mathematical and physical board for gas-water detection.

The Puguang Gas Field, located in the northeastern part of the Sichuan Basin, is a large-scale, fully developed, high-sulfur, ultra-high-pressure unconventional carbonate gas field in China. The main producing reservoir layers are the Feixianguan Formation, with burial depth of 5900 meters and thickness of 400 meters about. Currently, the Puguang Gas Field has entered the middle and later development stage. Water flooding is extremely common and has a serious impact on gas production. It is urgent to study the water flooding patterns in the reservoir and understand the distribution of formation water. This information is crucial for logging production control and development drilling. To address this, test on the joint detection of gas and water using integrated with LOTEM, seismic, and well logging data has been conducted in the Puguang Gas Field. Firstly, 19 survey lines were arranged in the main structural area of the Puguang Gas Field, totaling 1,138 measurement sites. The line interval is 200 meters, and the site interval is 50 meters, covering an area of 56.25 square kilometers. The data acquisition overcame the complex terrain conditions and the reliable LOTEM data had been obtained by increasing the transmitter current and extending the observation time. Secondly, based on well logging and seismic data, a spatially constrained initial model for LOTEM data inversion was established. In the inversion objective function, a cross-gradient term of the well-seismic spatial constraint model was added, which resulted in high spatial resolution and accuracy in the inversion of resistivity and polarization models. Finally, based on the pre-existing 3D seismic data and static and dynamic production data of gas wells in the testing area, the identification of gas and water at the edge of the main

structure of Puguang Gas Field and the analysis of the spatial distribution characteristics of the leading edge were carried out.

RESULTS and DISCUSSION

The specific results are as follows:

(a) The electrical characteristics of the Feixianguan reservoir show significant variations when it contains fluids. The variation pattern of resistivity is as follows: the resistivity of the dry layer is greater than that of the layer bearing gas or gas-water mixture or water. The polarization characteristics are as follows: The polarizability of the aquifer, dry layer, and gas layer is the highest, while the polarizability of the gas layer is lower. Based on these observations, a gas-water identification model was established for this area.

(b) With the well and seismic constrained LOTEM multi-parameter inversion and the seismic parameters inversion, time profiles and contour maps of sensitive parameters for the I to VI sequences of Feixianguan formation were obtained. Based on the gas-water distribution data from multiple production wells, the Q coefficients were calibrated, and a Q interpretation template was established. It was determined that when Q is less than 0.4, it indicates a water-invasion layer, when Q is between 0.4 and 0.6, it indicates a gas-water coexisting layer, and when Q is greater than 0.6, it indicates a gas layer or a dry layer. This model provides a basis for the quantitative interpretation of gas content detection analysis in the testing area.

(c) In terms of physical properties, sequences I, II, and III have relatively better physical properties than sequences V and VI. From a plane perspective, the physical properties near the Puguang Fault and in the northeast are poor. Vertically, the I, II, IV, and V sequences exhibit low resistivity, with the III sequence having the lowest resistivity, and the VI sequence showing relatively higher resistivity. The I, II, IV, and V sequences have high polarizablity, while the III and VI sequences have relatively lower polarizability. From a horizontal perspective the properties of the northeastern part are relatively poor. The central and southeastern parts exhibit characteristics of medium to low resistivity, while the northeastern and northwestern parts have higher resistivity. The central and southeastern parts show high anomalies in polarization rate, while the northeastern and northwestern parts have lower polarizablty.

(d) The Q planar distribution maps of the I-VI sequences indicate that water invasion occurs from the east and southeast, with the water body advancing towards the P103-4, P103-1, P105-2, and PG4 lines. The water body exhibits a trend of north-northeast to south-southwest, with a width varying between 1.5 to 2.0 km. The width of the gas-water interface varies between 200 to 500 m. The sequences with faster water invasion are I, II, III, and V, while the V and VI sequences, characterized by higher elevation and poorer properties, exhibit slower westward water invasion.

After the completion of the test, the gas field manager arranged the P103-2C lateral drilling near the P103-4 well, targeting the Feixianguan Formation reservoir. The logging results show that the area with high Q value anomalies is distributed in the IV-VI sequence area in the northwest of the survey line, which is a gas producing area. The area with medium to low anomalies in Q-value is distributed in the southeastern part of the I-III sequences, primarily representing a gas-water

transition zone. The correctness of its interpretation results was verified by P103-2C lateral drilling.

CONCLUSION

We define the gas-water identification factor Q based on the linear coupling of the main sensitive parameters, including electrical resistivity, polarization, seismic attribute parameters (Vp/Vs ratio, phase, and formation dip angle), and a technology of gas-water detection combing seismic and LOTEM are proposed based on five sensitive parameters of electrical resistivity, polarization, Vp/Vs ratio, seismic phase, and formation dip angle. The correctness of its interpretation results was verified by drilling well.