CO₂-Containing Reservoir Evaluation Based on the Joint Inversion of Nuclear Logs and Resistivity Logs: A Case Study of Ultrahigh-Temperature and High-Pressure Gas Reservoirs in the Yinggehai Basin, China

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ABSTRACT: Due to the unique characteristics of reservoirs in the Yinggehai Basin in the South China Sea, such as high temperature and high pressure (HPHT), low porosity, low permeability, complex pore structure, and high lime content, the log responses of these reservoirs have very complex characteristics, which makes it difficult to evaluate reservoir parameters accurately. In addition, most reservoirs in Ledong Block of the Yinggehai Basin in the South China Sea contain CO₂, posing great difficulties for subsequent exploration and development. Accurate evaluation of CO₂ layers is of paramount importance for the development of oil and gas fields. In this study, we used a method for the joint inversion of multiple well logs to evaluate the reservoirs and determine CO₂ saturation level and other formation parameters. We optimized the joint inversion model based on the characteristics of the reservoirs in the Yinggehai Basin and adjusted the forward simulation model to consider the effects of high temperature and high pressure on gas density. In view of high lime content in the formations in this area, we adjusted the resistivity forward simulation model to consider the effect of lime content. The inversion results show that the values of porosity, permeability, and water saturation level obtained through inversion are largely consistent with the core data. The CO₂ saturation level determined through joint inversion is 22%, which represents a deviation of less than 10% from the drilling system testing (DST) result, indicating that the joint inversion method is accurate. The error in the water saturation level determined through the joint inversion method is smaller than that in the calculated results from conventional multimineral inversion models. We performed forward simulation of the results calculated with the joint inversion method and compared the results of forward simulation with actual log curves. For the sandstone interval, the results of forward simulation are largely consistent with the actual log curves, indicating that the joint inversion method is accurate. In summary, the method presented in this paper can accurately determine reservoir parameters and provide strong support for the exploration and development of oil and gas fields in the Yinggehai Basin in the South China Sea.

1. INTRODUCTION
The accurate evaluation of reservoir parameters such as mineral composition, fluid saturation, and porosity is the main challenge faced by the oil and gas industry. Accurate mineral composition evaluation combined with geological knowledge can be performed to determine perforation interval and analyze reservoir characteristics, thus providing effective support for making decisions on the exploration and development of oil and gas fields. The Yinggehai Basin is a typical example of ultrahigh-pressure basins in China. HuangLiu Formation and Meishan Formation, which are main target intervals in the basin, are high-temperature and high-pressure (HPHT) formations. The reservoirs in this area are subject to strong diagenesis and generally characterized by low porosity, low permeability, complex pore structure, and high lime content. Under the combined influence of multiple factors, the log responses of these reservoirs have very complex characteristics, which brings difficulties to the accurate evaluation of reservoir parameters. In addition, most reservoirs in the Yinggehai Basin in the South China Sea contain CO₂. The log responses of CO₂ are similar to those of...
hydrocarbon gases, which makes it difficult to measure the CO$_2$ saturation level with traditional logging techniques and poses great difficulties for subsequent hydrocarbon exploration and development. The main method for identifying CO$_2$ from hydrocarbon gases is to combine neutron logging with density logging, draw cross-plots, and then calculate the CO$_2$ saturation level using empirical equations. Combined with various logging data, the optimization method based on the linear volume model is used to calculate CO$_2$ saturation. However, these methods are only suitable for particular blocks, and the empirical equations cannot meet the varying requirements for reservoir evaluation in different areas. Different nuclear logging parameters are also used for the qualitative identification of CO$_2$, but the method based on these parameters cannot evaluate the CO$_2$ saturation level accurately.

The traditional constrained linear inversion methods mostly assume that there is a linear or quasi-linear relationship between formation properties and log curves, but they do not consider the influence of thin layer, mud invasion, and heterogeneity on the calculation. The traditional methods can obtain accurate estimates in many simple cases, but they may fail in evaluating complex reservoirs. The nonlinear joint inversion method based on multiple well logs has been widely used to evaluate complex reservoirs and determine mineral content, fluid content, and other reservoir parameters. This method has achieved good results in both vertical and horizontal wells. It can be used to accurately evaluate various complex formations, such as thinly bedded and interbedded formations, and to determine total organic carbon (TOC) content, porosity, mineral composition, fluid composition, and other formation parameters. The method for the rapid forward simulation of nuclear logs based on the flux sensitivity equation was first proposed, making it possible to conduct the inversion of nuclear logs. Then, neutron and density logs were used in conjunction with resistivity logs for joint inversion in order to determine the water saturation level and other parameters of thinly bedded formations. In addition, the joint inversion method was also used for the inversion of density image logs in high-angle and horizontal wells, and the use of this method improved the ability to interpret LWD (Logging While Drilling) density measurements in high-angle and horizontal wells. Besides density and resistivity logs, gamma ray (GR) logs were also introduced for joint inversion. This method achieved good results in thinly bedded clastic rock formations. The method for the rapid simulation of pulsed neutron capture logs was established, laying a solid foundation for the development of inversion methods combining pulsed neutron capture logs with other logs. The method for the joint inversion of multiple well logs including neutron, GR, photoelectric factor (PEF), density, and resistivity logs was used to estimate the TOC content in shale gas reservoirs. The impact of borehole conditions was considered to improve the accuracy of the rapid joint inversion method based on nuclear and resistivity logs. The improved method was used to evaluate porosity and fluid parameters in large-angle and horizontal wells, achieving accurate measurement of fluid saturation level. An additional inversion method based on spectral mixing laws and argillaceous sandstone saturation model was used to quantify the petrophysical properties of laminated formations with a thickness smaller than the logging tool’s vertical resolution and perform quantitative analysis of the petrophysical properties of hydrogen-containing formations. The rapid simulation and
inversion method based on the energy spectrum of gamma rays was used to interpret the measurements in high-angle and horizontal wells penetrating thinly bedded formations. Nuclear magnetic resonance (NMR) logs were used in combination with logging parameters such as density, Sigma (neutron capture cross section), HI (hydrogen index), migration length, PEF, and neutron porosity measurements for joint inversion. The combination of the quasi-Newton methods and Markov Chain Monte Carlo sampling methods (QNMC-MCMC) was used to improve the accuracy of joint inversion and evaluate formation properties. However, the methods mentioned above did not consider the effects of high temperature and high pressure on the inversion process, and they were not used to evaluate CO₂ saturation level.

In this study, a joint inversion evaluation method was used to evaluate CO₂-containing reservoirs, and the joint inversion of neutron, density, GR, and resistivity logs was performed to evaluate the CO₂ content and other parameters of the reservoirs in the Yinggehai Basin. We modified the joint inversion model based on the characteristics of these reservoirs to consider the effects of high temperature and high pressure on gas density, adjusted the resistivity simulation model in consideration of high lime content in the target area, and evaluated the reservoirs by performing joint inversion based on multiple logging techniques. The joint inversion method was used to determine various formation parameters by performing the rapid simulation of nuclear and resistivity measurements and comparing the simulated log curves with actual log curves. The effectiveness of the joint inversion method was verified by analyzing the results of its application in different wells in Ledong Block of the Yinggehai Basin in the South China Sea.

2. GEOLOGICAL SETTING

The Yinggehai Basin is a typical example of ultrahigh-pressure basins in China. With the progress of exploration and development, a number of large gas fields have been discovered in Dongfeng Block (DF), Ledong (LD) Block, and other areas in the Yinggehai Basin. In recent years, new breakthroughs have been made in the exploration of gravity flow marine sand bodies in the Miocene Huangliu Formation of LD Block, and a large gas field has been discovered in LD10 area. The Yinggehai Basin is a NW-SE-striking, Cenozoic transtensional large gas field has been discovered in LD10 area. The formation of this area is located in the slope zone between the diapiric structure and the Yingdong slope in the central sag (as shown in Figure 1). Most exploration wells have been drilled in LD Block in the Yinggehai Basin. Huangliu Formation and Meishan Formation area are two main target intervals buried at depths of nearly 4000 m with a formation temperature of nearly 200 °C, formation pressure of 100 MPa, maximum pressure coefficient of 2.3, and very harsh borehole conditions. These harsh conditions result in low abundance of logging data from the wells in this area. The reservoirs in this area are subject to strong diagenesis and generally characterized by low porosity, low permeability, complex pore structure, and high lime content. Under the combined influence of multiple factors, the log responses of reservoirs in this area have very complex characteristics. The DST data of this area shows that the results of gas testing in the same formation vary by well, indicating that the electrical responses of gas layers in this area are very complex. Moreover, there are no apparent rules governing the distribution of interwell and interlayer fluids in this area, which makes it very difficult to identify the properties of reservoir fluids. With the continuous progress of exploration and development activities in the western South China Sea, it is becoming more and more difficult to identify the properties of hydrocarbon reservoirs in this area and evaluate these reservoirs based on well logs. This brings more uncertainties to the interpretation of well logs at the early exploration and development stage and fine reservoir evaluation at later stages performed by researchers and makes it impossible to provide guidance for making decisions on drilling operations and evaluating hydrocarbon reservoirs in real time.

3. METHODOLOGY

3.1. Joint Inversion Method Combining Nuclear and Resistivity Logs. Heidari et al. (2012) introduced a nonlinear inversion-based interpretation method for estimating mineral composition, porosity, and fluid saturation level in thinly bedded, argillaceous sandstone, and carbonate formations based on multiple well logs. The inversion process consists of several steps. The first step is to stratify the formation based on log curves. The second step is to determine the initial value of parameter x of the rock physics model. This initial value is usually obtained by conventional log interpretation methods or from core data/X-ray diffraction (XRD) data. The third step is to build the model using the initial values of x for all layers and obtain the log responses (density, neutron, gamma ray, and resistivity log responses) for each layer using the rapid simulation method. The last step is to adjust the initial model based on the results of comparison between the simulated and measured responses and find the optimal solution. Equation 1 below is the objective equation for nonlinear inversion. It can be used to determine a set of model parameters for each formation by minimizing the objective equation.

\[
C(x) = ||W_d \cdot (d(x) - d_m)||^2 + \alpha^2 ||x||^2, \quad 0 \leq x_1 \leq 1,
\]

where \(W_d\) is the weight of data, \(d\) is the simulated log response, \(d_m\) is the measured log response, \(\alpha\) is the damping factor, \(x\) is the parametric vector of the rock physics model, and \(i\) is the number of formations. \(x\) can be expressed as

\[
x = [C_{i1}, C_{i2}, \ldots, C_{ip}, C_{ik}, \phi_i, S_w]^T,
\]

where \(C_{i1} - C_{ip}\) denote the contents of different mineral components, \(C_{ik}\) is the shale content, \(\phi_i\) is the formation porosity, and \(S_w\) is the water saturation level. The simulated log response \(d\) can be expressed as

\[
d = [\text{neutron porosity, density, resistivity, gamma ray}]^T,
\]

Equation 3 is constrained by:

\[
\sum_{i=1}^{n} C_i + C_{ik} + \phi_i = 1.
\]

The Levenberg–Marquardt method is used to minimize eq 1 to obtain the optimal \(x\) value. The density and GR correlation values in the Jacobian matrix are obtained.
according to the linear correlation between the formation’s petrophysical properties and measured logs. The resistivity correlation value in the Jacobian matrix is obtained using the finite difference method. The neutron porosity correlation value in the Jacobian matrix is obtained using the method proposed by Ortega and Torres-Verdín (2015). The stabilization parameter $\alpha$ in eq 1 is automatically selected by the L-curve method.

3.2. Optimized Rock Physics Volume Model. In this study, the inversion model proposed by Heidari et al. (2012) was modified considering the effects of temperature and pressure on gas density and the impact of lime content on resistivity logging to make it suitable for the evaluation of complex reservoirs in the Yinggehai Basin. The modified model was used to evaluate the complex reservoirs in this area, identify the properties of reservoir fluids, and accurately determine various formation parameters, such as porosity, permeability, water saturation, lime content, and CO$_2$ content.

The rock physics volume model for CO$_2$-containing formations is shown in Figure 2. This model consists of matrix minerals, clay minerals, and pore fluids. Pore fluids include water, CO$_2$, and CH$_4$. The value of gas density under the HPHT conditions of the Yinggehai Basin is greatly different from that at normal temperature and pressure. Such a difference has a certain impact on density logging and neutron logging and may result in errors in the results of well log interpretation. We determined the temperature and pressure conditions at different depths based on the geothermal gradient and pressure gradient in the target area, calculated the densities of CO$_2$ and hydrocarbon gases using the method proposed by Kennedy (1954) and Cristancho et al. (2010), and further considered the impact of changes in gas density on density logging and neutron logging. The main rock mass in the Yinggehai Basin is sandstone with high lime content. Therefore, quartz and calcite were used as the main matrix minerals.

Figure 2. Model of CO$_2$-containing reservoirs.

The first step for nonlinear joint inversion is to stratify the formation. In this study, stratification is achieved by determining the boundaries of the foundation based on the inflection points of density, gamma, and array-induction apparent resistivity log curves. The inflection point in the logging curve is used to indicate the formation boundary. The next step is to determine the initial value of parameter $x$ for each layer of the rock physics model. This initial value is usually obtained by conventional log interpretation methods or from core data/X-ray diffraction (XRD) data. We have adjusted the joint inversion model based on the geological characteristics of the Yinggehai Basin. Equation 2 can be rewritten as

$$x = [C_{\text{sand}} + C_{\text{limer}}] \phi_l S_{\text{CO}_2} S_{\text{sh}}^\beta,$$

where $C_{\text{sand}}$ is the sandstone content in the formation, $C_{\text{limer}}$ is the lime content in the formation, and $S_{\text{CO}_2}$ is the CO$_2$ saturation level. The rapid forward simulation method is used to calculate different log responses in the formation based on mineral content and fluid content in $x$. For density logging, the density of each layer is calculated using the rock physics model as follows:

$$\rho_b = \sum_{i=1}^{n_c} (C_i \rho_i) + \rho_{b0} C_{\text{sh}},$$

where $\rho_i$ is the density of various minerals, $\rho_{b0}$ is the fluid density, $n_c$ is the number of matrix minerals, and $\rho_{b0}$ is the density of clay minerals. Fluid density is calculated as follows:

$$\rho_f = S_w \rho_w + (1 - S_w) (S_{\text{CO}_2} \rho_{\text{CO}_2} + S_{\text{CH}_4} \rho_{\text{CH}_4}),$$

where $S_w$ is the water saturation level, $\rho_{\text{CO}_2}$ is the CO$_2$ density, $\rho_{\text{CH}_4}$ is the CH$_4$ density, and $\rho_w$ is the water density. The XRD data shows that the main clay minerals in the target area are illite and montmorillonite. To simplify the calculation process, the density of the illite–montmorillonite mixed layer is used to represent shale density. The rapid forward simulation method is used to perform the rapid simulation of density log responses.

The rapid simulation of neutron logs is mainly achieved by calculating the migration length. According to the model shown in Figure 2, the migration length can be expressed as

$$\xi = \beta [S_w \xi_w + (1 - S_w) (S_{\text{CO}_2} \xi_{\text{CO}_2} + S_{\text{CH}_4} \xi_{\text{CH}_4})] + (1 - \beta) \xi_{5m},$$

where $\xi$ is the migration length, $\xi_w$ is the migration length for pure water, $\xi_{\text{CO}_2}$ is the migration length for CO$_2$, $\xi_{\text{CH}_4}$ is the migration length for CH$_4$, and $\xi_{5m}$ is the migration length for matrix minerals. $\beta$ is a nonlinear coefficient relevant to shale content:

$$\eta = 0.5(1 - C_{\text{sh}}) + 0.8 C_{\text{sh}}.$$
\[ R_t = \frac{1}{\left( \frac{V_{sh}}{R_{sh}} - \frac{V_{ca}}{R_{ca}} + \phi_i^{0.5m} \right)^2 S_w^n} \]  

(10)

where \( \phi_i \) is the total porosity of the formation, \( R_w \) is the resistivity of formation water, \( R_{sh} \) is the resistivity of clay, \( R_t \) is the resistivity of the formation, \( V_{sh} \) is the volume of clay mineral, \( V_{ca} \) is volume of lime mineral, \( a \) is a coefficient, \( m \) is the cementation index, \( n \) is the saturation index, and \( d \) is the shale content index. The rapid simulation of resistivity curves is achieved based on the resistivity of each layer. \(^{13} \) The rapid simulation of GR logs is achieved using the method proposed by Mendoza et al. (2006) based on the mineral composition of each layer. \(^{31} \) The resistivity, density, and migration length of each layer are calculated using eqs 10, 6, and 8, respectively. Log response \( d \) of each layer is determined using the rapid simulation method based on the parameters of each layer. In this paper, the initial values of petrophysical parameters are retrieved by the following methods: (1) XRD/Core data; (2) conventional petrophysical interpretation and linear multimineral solver. The initial value of CO\(_2\) saturation is calculated using the method proposed by He et al. (2016). \(^{7} \) The simulated log response \( d \) is compared with the actual log response, \( x \) is adjusted to minimize the objective eq 1, and then various parameters of each layer are calculated.

4. RESULTS AND DISCUSSION

Huangliu Formation is the main target interval in Ledong Gas Field. The layers encountered during drilling through the first member of Huangliu Formation are classified into four groups from top to bottom, including H1I, H1II, H1III, and H1IV. The gas layers encountered during drilling through the second member of Huangliu Formation are classified into five groups from top to bottom, including H2I, H2II, H2III, H2IV, and H2V.

Among these groups, H1IV, H2II, H2II, H2III, H2IV, and H2V are gas-bearing intervals (as shown in Figure 3). In
general, layer thickness and sand body thickness gradually decrease from bottom to top (from H2V to H2I).

The results of conventional petrophysical analysis of cores show that the distributions of porosity and permeability in the second member of Huangliu Formation are positively skewed; the primary porosity peaks range between 10.0% and 12.0%, the primary permeability peaks range between 0.64 and 1.28 mD; for the sandstone samples taken from 106 reservoir intervals, porosity ranges from 8.2% to 14.5%, the median of porosity is 10.3%, and the average porosity is 10.3%; permeability ranges from 0.3 to 33.7 mD, the median of permeability is 0.8 mD, and the average permeability is 2.7 mD. These results indicate that the second member of Huangliu Formation is characterized by low porosity and ultralow permeability (as shown in Figure 4).

This formation has a high pressure coefficient (ranging between 2.174 and 2.305, indicating that the formation is an ultrahigh-pressure system), and the original formation pressure ranges between 84.289 and 93.598 MPa. The original formation temperature ranges between 190.11 and 208.63 °C, and the geothermal gradient is 4.89 °C/100 m, indicating that the formation is an ultrahigh-temperature system. In summary, Huangliu Formation in Ledong 10-1 Gas Field is an elastic water drive-lithologic gas reservoir under ultrahigh pressure and ultrahigh temperature conditions. Exploration practices reveal that the flow channels in Huangliu Formation provide unique conditions for the accumulation of natural gas, the primary flow channels for the accumulation of natural gas have undergone multistage sand body superposition, and the gas-field and gas-water relations are complex. In Huangliu Formation, deep-sea fan sediments have been deposited in slope settings and subjected to late-stage tectonic modification. In terms of lithology, Huangliu Formation is mainly composed of medium- to fine-grained sandstones. The reservoirs in this formation are highly heterogeneous formations with low porosity and low-to-ultralow permeability. We processed the log data of two wells in a gas field in LD Block by means of

Figure 5. Joint inversion results for Well 1.

Figure 6. Comparison between the inversion results relevant to the water saturation level and core data.
forward simulation and inversion, compared the inversion results with core analysis results to verify the accuracy of inversion results, calculated the CO$_2$ saturation level using the joint inversion method and conventional multimineral models, and compared the calculated results to verify the accuracy of the joint inversion method relative to that of conventional methods.

4.1. Field Example 1. The parameters for the inversion process were set as described below. The GR threshold for lithologic classification was set to 100 so that geological units could be identified as sandstones when the value is smaller than 100 and identified as mudstones when the value is larger than 100. If there are CAL (caliper log) curves, the CAL curves should be used as constraints. If there are no CAL curves, the drill bit size should be used as the constraint. The formation was stratified into a number of layers both automatically and manually based on changes in GR, density, and resistivity curves. The new joint inversion method was used to determine the porosity, permeability, water saturation level, lime content, and CO$_2$ content of the formation. The main problems to be solved for this well are the accurate measurement of water saturation level and quantitative analysis of CO$_2$ content.

Figure 7 shows the results of joint inversion for Well 1. Track 1 is for GR curves. Track 2 is for resistivity curves. Track 3 is for neutron curves and density curves. Track 4 is for depth curves. Track 5 is for inversion results relevant to shale
content. Track 6 is for results relevant to porosity. The red lines represent core data. It can be seen that the porosity values determined through inversion are generally consistent with the core data. Track 7 shows the inversion results relevant to permeability and the core data. Like the case with Track 6, the inversion results relevant to permeability are consistent with the core data. Track 8 shows the inversion results relevant to water saturation level and the core data. Figure 6 shows the water saturation level determined through joint inversion and the actual water saturation level indicated in the core data. In Figure 6, the abscissa represents the water saturation level indicated in the core data, and the ordinate represents the deviations of the water saturation levels calculated using the joint inversion method and conventional multimineral models from the core data. The red dots represent the differences between the water saturation levels determined through joint inversion and those indicated in the core data, and the blue dots represent the differences between the water saturation levels determined using conventional interpretation methods and those indicated in the core data. In general, compared with the results obtained from conventional methods, the water saturation levels determined through joint inversion are more consistent with the core data, except for one data point. In other words, the results of joint inversion are more accurate than those obtained by conventional methods. Track 9 shows the calculated results of lime content. Track 10 shows the inversion results relevant to the CO\textsubscript{2} saturation level. The CO\textsubscript{2} saturation level calculated through joint inversion is about 44.8%, and the CO\textsubscript{2} saturation level measured by DST is about 41%, indicating that the calculated result is largely consistent with the DST result.

To further verify the accuracy of the results from multidimensional joint inversion, we performed forward simulation of the formation parameters calculated and determined through joint inversion. The results of forward simulation are shown in Figure 7. Track 1 and Track 2 in Figure 7 show the GR curves and depth curves, respectively. Track 3 shows the actual resistivity curves of electromagnetic wave logging-while-drilling (LWD) at varying measuring depths. Track 4 shows the electromagnetic wave LWD resistivity curves obtained by performing forward simulation of the inversion results. Track 5 is for the comparison of resistivity curves. P40H represents the measured resistivity curves, and PH40S represents the simulated resistivity curves. It is obvious that the simulated resistivity curves are largely consistent with the measured resistivity curves. Track 6 is for the comparison of density curves. RHOB represents the measured density curves, and RHOBS represents the simulated density curves. It can be seen that there are certain differences between the simulated and measured density curves for the mudstone interval. Track 7 is for the comparison of neutron porosity curves. TNPH represents the measured neutron porosity curves, and TNPHS represents the simulated neutron porosity curves. The simulated neutron porosity curves are consistent with the measured neutron porosity curves. The comparisons above show that there are great differences between the simulated and measured results for the mudstone interval. The results of forward simulation relevant to resistivity and neutron responses are basically consistent with the curves of measured data, and the calculated results of density are slightly different from the measured data. In summary, the results of forward simulation demonstrate the accuracy of the results from joint inversion.

4.2. Field Example 2. The main problem to be solved for this well is the quantitative analysis of CO\textsubscript{2} content. The datasheet of pressure measurements shows that the average formation pressure is 13,350 psi, the drill pipe pressure is 13,546 psi, and the average pressure coefficient is 2.29. The parameter settings for the inversion process and the stratification method for this well are the same as those for Well 1. Figure 8 shows the results of joint inversion of LWD measurements at the 4092−4119 m interval of H2III in Well 2. The tracks in Figure 8 represent the same formation parameters as those indicated in Figure 5.
The CO₂ content calculated by conventional interpretation methods is about 70%, while the CO₂ content measured by DST is about 16.39%. In comparison, the average CO₂ content determined through joint inversion is 22.1%, which is largely consistent with the DST result. The comparison between the inversion results and the results of core tests indicates that the joint inversion method is highly accurate in determining the shale content, porosity, permeability, and water saturation level.

We performed forward simulation of the formation parameters determined through joint inversion, obtained the log curves corresponding to the time of measurement of the logging tool in the inversion model, and compared these curves with the measured data to verify the accuracy of inversion results. The curves compared include resistivity, neutron porosity, and density curves. The results of forward simulation are shown in Figure 9.

In Figure 9, Track 3 shows the actual resistivity curves of electromagnetic wave LWD at varying measuring depths, and Track 4 shows the LWD resistivity curves obtained by performing forward simulation of the inversion results. Track 5 is for the comparison of resistivity curves. P40H represents the measured resistivity curves, and PH40S represents the simulated resistivity curves. Track 6 is for the comparison of density curves. RHOB represents the measured density curves, and RHOBS represents the simulated density curves. Track 7 is for the comparison of neutron porosity curves. TNPH represents the measured neutron porosity curves, and TNPHS represents the simulated neutron porosity curves. It can be seen that the simulated resistivity, density, and neutron porosity curves are basically consistent with the curves of measured data. By comparing the results shown in Figure 9, it can be known that there are great differences between the simulated and measured results for the mudstone interval. The results of forward simulation relevant to resistivity, density, and neutron responses are basically consistent with the curves of measured data, indicating that the results of joint inversion are accurate.

5. CONCLUSIONS

Considering the unique characteristics of the reservoirs in LD Block of the Yinggehai Basin in the South China Sea, we performed the joint inversion of density, neutron porosity, GR, and resistivity logs to determine various formation parameters, including porosity, permeability, lime content, shale content,
and CO₂ saturation. We adjusted the joint inversion model to consider the effects of temperature, pressure, and lime content, obtained simulated log curves by performing rapid forward simulation using the modified model, and compared the simulated log curves with the actual log curves. Then, we minimized the objective equation and determined various formation parameters.

The inversion results with respect to porosity, permeability, and water saturation level are basically consistent with the core data. We have compared the water saturation levels determined through joint inversion with those calculated by conventional multimineral models. It has been found that the errors in the results of joint inversion are smaller than those in the results from conventional interpretation methods. The CO₂ saturation level measured by DST is 16.39% and the CO₂ saturation level determined through joint inversion is 22%, representing an error of joint inversion is less than 10% compared to the DST result. In addition, we performed forward simulation of the results of joint inversion and compared the results of forward simulation with the actual log curves. The results of forward simulation for the mudstone interval are different from the actual log curves. For the sandstone interval, the results of forward simulation are largely consistent with the actual log curves, indicating that the joint inversion method is accurate. After its successful application in the Yinggehai Basin, the joint inversion method has solved the problems in the evaluation of complex reservoirs in the target area and provided strong support for determining the hydrocarbon producing zones and making decisions on drilling operations during subsequent exploration and development.

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**Notes**

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