Optimized log evaluation method of unconsolidated sandstone heavy oil reservoirs

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Abstract

It's very difficult to make log interpretation for unconsolidated sandstone heavy oil reservoirs because of its complex poroperm characteristics and special fluid property. Multi-mineral log interpretation method can utilize various logging information effectively to obtain reservoir parameters accurately. The reservoir in A1 area is mainly of unconsolidated sandstone with complex mineral component. The reservoir porosity and component concentration of multiple minerals can be computed by optimized method of multi-mineral model, and the permeability can be computed by the Scheidger Formula, which show the computational solution and tendency of variation have good coincide with core analysis. With indication of oil and gas identifying the heavy oil reservoirs, log interpretation coincidence rate can be enhanced effectively by mud invasion information, providing dependable reference for scientific and appropriate exploration of heavy oil reservoirs in A area.

Keywords

Unconsolidated; Sandstone; Multi-mineral log interpretation method; Heavy oil.

1. Introduction

It's extremely difficult to identify the fluid property in the reservoir and make production forecast because of the non-convention and restricted development technique of heavy oil reservoirs [1-2]. So identifying the fluid property and forecasting the production of heavy oil reservoirs correctly can not only certificate the exploration activity outcome, but also provide geological basis to draw up the oil/gas field development program and ameliorate the engineering measures[3-5]. It is one of difficulties for log interpretation technique at present to analyze and evaluate the heavy oil reservoirs by well logging data.

So far log interpretation for unconsolidated sandstone heavy oil reservoirs is still in an exploratory stage[6], and there is no systematic and mature interpretation method, in spite of the experiences and method summing up by combining the characteristics of the specific region. Because of the complex mineral composition of unconsolidated sandstone heavy oil reservoirs and the difference of fluid characteristics between heavy oil and unconventional hydrocarbon, conventional log interpretation method can't be adopted extensively and general for model interpretation, parametric calculation and fluid recognization for the heavy oil reservoirs, so it is of hardship to evaluate the formation of multiple minerals effectively without choosing interpretation model flexibly[7-11]. Based on the strong heterogeneity and fluid properties of unconsolidated sandstone heavy oil reservoirs, multi-mineral analytic method is adopted to evaluate the unconsolidated sandstone heavy oil reservoirs, obtaining all kinds of formation parameter of reservoirs accurately, enhancing the capability of log interpretation for reservoirs apparently and providing much more dependable foundation for scientific and appropriate development of heavy oil reservoirs.

2. Optimized multi-mineral analytic method

2.1 Modelling

Take the formation of complex lithology as a unit composed of several homogeneous parts: matrix minerals ($\sum V_{mai}$), clay (V_{cl}) and pores (ϕ). Several mineral compositions are chosen to set four reservoir parameters, and the unknown vectors are:

$$X = \left(\phi\ ,\ S_w,\ V_{cl},\ S_{xo}, \sum_{i=1}^{m} V_{mai} \right) \tag{1}$$

m-the quantity of matrix minerals, S_w -water saturation, S_{xo} -water saturation in the flushed zone.

Matrix minerals stand for quartz, calcite, dolomite or other minerals. Physical model of rock bulk can express the response equation of formation for logging instruments. Such as, for the formation containing *m* minerals (number *m* stands for pores), density log ρ_b can be formulated by

$$\rho_b = \rho_1 V_1 + \rho_2 V_2 + \cdots + \rho_j V_j + \cdots + \rho_\phi V_\phi$$

$$1 = V_1 + V_2 + \cdots + V_j + \cdots + V_\phi \tag{2}$$

V_j -Volume content of mineral *j* in the formation, ρ_j -Volume density of mineral *j* in the formation, V_ϕ -Pore volume of mineral *m* in the formation, ρ_ϕ - Pore density of mineral *j* in the formation.

Like the log response equation above, logging traces (GR, AC, and CNL) can also be relevantly formulated by (assuming that there are *N-1* logging traces, *m* minerals content to be computed, including pore volume, and $N \geq m$).

$$\begin{bmatrix} L_1 \\ L_2 \\ \vdots \\ L_i \\ \vdots \\ L_{N-1} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1j} & \cdots & P_{1\phi} \\ P_{21} & P_{22} & \cdots & P_{2j} & \cdots & P_{2\phi} \\ & & \vdots & & & \\ P_{i1} & P_{i2} & \cdots & P_{ij} & \cdots & P_{i\phi} \\ & & \vdots & & & \\ P_{(N-1)1} & P_{(N-1)2} & \cdots & P_{(N-1)j} & \cdots & P_{(N-1)\phi} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_j \\ \vdots \\ V_\phi \end{bmatrix} \tag{3}$$

L_i - values of logging traces (i≤N-1), P_{ij} - log response parameters of minerals, V_j -mineral volume content (j<m).

And the equilibrium equation $V_1 + V_2 + \cdots + V_j + \cdots + V_\Phi = 1$ can make up a lineal overdetermined set containing *N* equations.

When computing the mineral component, what needed to do is to solve the above linear set of equations under the constraint condition ($V_j \geq 0$), because of the equilibrium equation being contained by the overdetermined equation set and holding large weighting coefficient .The model analysis procedure can pull the solutions outside back to the constraint range, by adopting exterior point penalty function to find the solution. And the object function is

$$f[V] = [PV - L]' W [PV - L] + V'RV \tag{4}$$

W- Weighting coefficient matrix.

The total error of each logging trace is transformed into weighting coefficient of the response equation in the model analysis procedure. And the penalty factor matrix ***R*** is a diagonal matrix (when $V_i \geq 0$, $R_{ii} = 0$; when $V_i < 0$, $R_{ii} > 0$).

The model analysis procedure is based on the iterative method that the constrained optimized solution is approximated by the unconstrained optimized solution step by step, and the optimized solution for overdetermined equation set with constraint conditions can be obtained after limited iterations. In summary, the multi mineral model can be expressed as a set of linear equations. The linear overdetermined equation set and constraint condition of inequality are PV-L=0 and V≥0, respectively; the objective function and its optimal solution are $f[V]=[PV-L]'W[PV-L]+V'RV$ and $V=[P'WP+R]^{-1}[P'WL]$, respectively.

According to the generalized inversion theory of Geophysics, based on the actual log values of the real response to the strata after the environmental impact correction, the optimized log interpretation feasibly chooses original value of territorial interpretation parameter basing the appropriate interpretation model and logging equation, and computes the homologous academic log value which will be compared with the actual log value. Then the optimized log interpretation will establish an objective function following the nonlinear weighting least square method, and constantly regulates the unknown reservoir parameters by optimized technique, minimizing the objective function until the academic log value sufficiently approximating the actual log value. Ultimately, the unknown quantity *X* on behalf of the computed academic log value is the result of optimized log interpretation, thoroughly representing the actual reservoir parameter.

Different from conventional log interpretation method, this method is a multi-dimensional information synthesis of all the well logging information, errors and geological experience in some areas by using the optimized mathematical method and carrying on the multi-dimensional processing, and the best interpretations will be obtained ultimately. The principle of this method is showed in Fig.1.

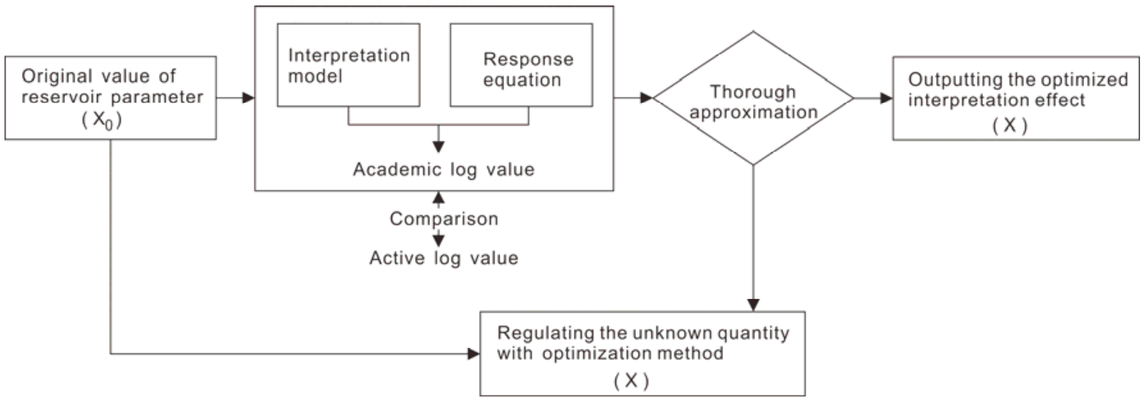

Fig.1 Optimized log interpretation rule of multi-mineral model

To sum up, the multi-mineral model is

Overdetermined linear equation set PV-L=0

Inequality constraints V≥0

Objective function $f(V)=(PV-L)'W(PV-L)+V'RV$ (5)

Optimal solution $V=(P'WP+R)^{-1}(P'WL)$

If N equals to M, the formula mentioned above can also be adopted.

2.2 Model analysis

Error analysis of the multi-mineral method and resolution ratio are very important. If a certain curve has low total error, its weighting coefficient will be high, and the curve will play a more important role in the object function. So when computing the mineral composition, the model analysis procedure will compute each academic bore log by the log response equation, then it will compare the academic logging traces with actual logging traces, analysis the errors and regulate the interpretation parameter, finally the mean deviation is

$$\delta^2 = \frac{1}{N-1}\sum_{i=1}^{N-1}\left(\frac{L_i - L_{it}}{\partial_i}\right) \tag{6}$$

L_{it} - Theoretical log value, L_i - Actual log value, ∂_i - Total log value. Computed δ is the minimal value of object function under the constraint conditions, and is a measure of the adopted model's data fitting approximation to the well log data.

In addition, the ability of logging traces to distinguish minerals is an important condition for selecting interpretation model, for example, the logging trace GR can distinguish clay and quartz, but not distinguish calcite and dolomite. And the resolution ratio ε indicates the differentiating ability of logging trace L to mineral V in model analysis. When processing the data with the single model or multi model, the model should be analyzed and then the resolution ratio ε can be computed. The resolution ratio ε is divided into levels: good (ε＜4), general (4＜ε＜5), poor (5＜ε＜6) and very poor (ε＞6). So when the value of ε is more than 6, reducing of mineral number in the model or increasing the types of logging traces should be choose to guarantee the exactitude of the interpretations. When processing practically, to rationally select the mineral assemblage and to adjust the theoretical value of the mineral log response will be the key factor to verify the exactitude of the multi-mineral model.

3. Interpretation model for parameters of heavy oil reservoir

The heavy oil reservoir in A area is mainly composed of lithic sandstones, and the water saturation can be directly calculated by Archie equation, due to the high viscosity of heavy oil and indistinct mud invasion. Permeability is the main parameter that determines whether the fluid can be extracted from the formation, and the Kozeny-Garman permeability formula proposed by Scheidger is much more applicable to compute the permeability of clastic porous formation, so the Kozeny-Garman permeability formula is adopted to compute permeability in this paper:

$$K = \frac{A\varphi^3}{(1-\varphi)^2 S_r} \tag{7}$$

K- Permeability, 10^{-3} μm^2; A- Empiric constant; φ- Porosity,%; Sr- Particle surface area of rock unit volume, mm^2. For the convenience of calculation, the formula above can be manipulated into:

$$K = \frac{\varphi^3}{(1-\varphi)^2} e^{(AF+\sum Bi+Vi)} \tag{8}$$

Vi- Mineral contents, %; Bi- Empiric constant; AF- Maximum content function of feldspar.

Because of the high viscosity and poor fluidity of heavy oil, the reservoir is not easily invaded by mud filtrate or has a shallow invasion depth during drilling. But the diameter of invasion (Di) and true formation resistivity (Rt) can be obtained by Latero-Log Deep Resistivity Log (RLLD), Latero-Log Shallow Resistivity Log (RLLS) and Micro-Spherically Focused Resistivity Log (RMSFL), qualitatively distinguishing the heavy oil reservoir and non-heavy oil reservoir. For RLLD and RLLS, mud invasion correction depends on the electrode coefficient and apparent resistivity, so Rt and Di can be computed by RLLD and RLLS. Formula of mud invasion adjustment for LLD and LLS is:

$$Di = D0\exp[2.617(\frac{RLLS - Rt}{RMSFL - Rt})] \tag{9}$$

KLLD- LLD electrode constant, KLLS-LLS electrode constant; D0- Measured caliper, m.

4. Application

Fig.2 shows comparison between the core data and the interpretations which are obtained from well A1 in A area by the interpretation model[2]. And it indicates that the lithology of intended interval is mainly composed of quartz and clay, and the computational solutions of porosity and permeability have a good match with the actual core data.

The interpretations indicate that the 1st interval and the 3rd interval are major oil layers both of which have analogous physical properties, oil-gas bearing properties and invasion depth; the bore log of invasion depth in the 6th column indicates that the invasion depth of the 1st and 3rd interval is less than that of the lower interval interpreted to be a aqueous layer, and the bore log of invasion depth computed in the oil layer interval makes no difference to that of the upper and lower mud intervals (being of no permeability, there is no invasion in mud interval), indicating that the actual invasion depth of oil layers at the intervals is shallow. And the oil-gas analysis manifests that there is much irreducible oil in the oil layer intervals mentioned above, so the 1st and 3rd interval are taken to be heavy oil layers. And well test for the 1st interval shows that 3.1 tons of crude oil and 0.4 tons of water can be produced each day.

So the 1st interval is considered a heavy oil layer according to the testing data and analytic data of crude oil, which is in accord with the log interpretation. Even though other intervals have not been perforated and tested for oil yet, for the 7th interval, the abnormal amplitude of spontaneous potential (SP) increases obviously and the resistivity decreases with mudstone being the baseline, indicating that the 7th interval is aqueous layer. Based on the analysis above, the computational solutions of porosity and permeability are compared with the core porosity and permeability, which is showed in Fig.3 and Fig.4.

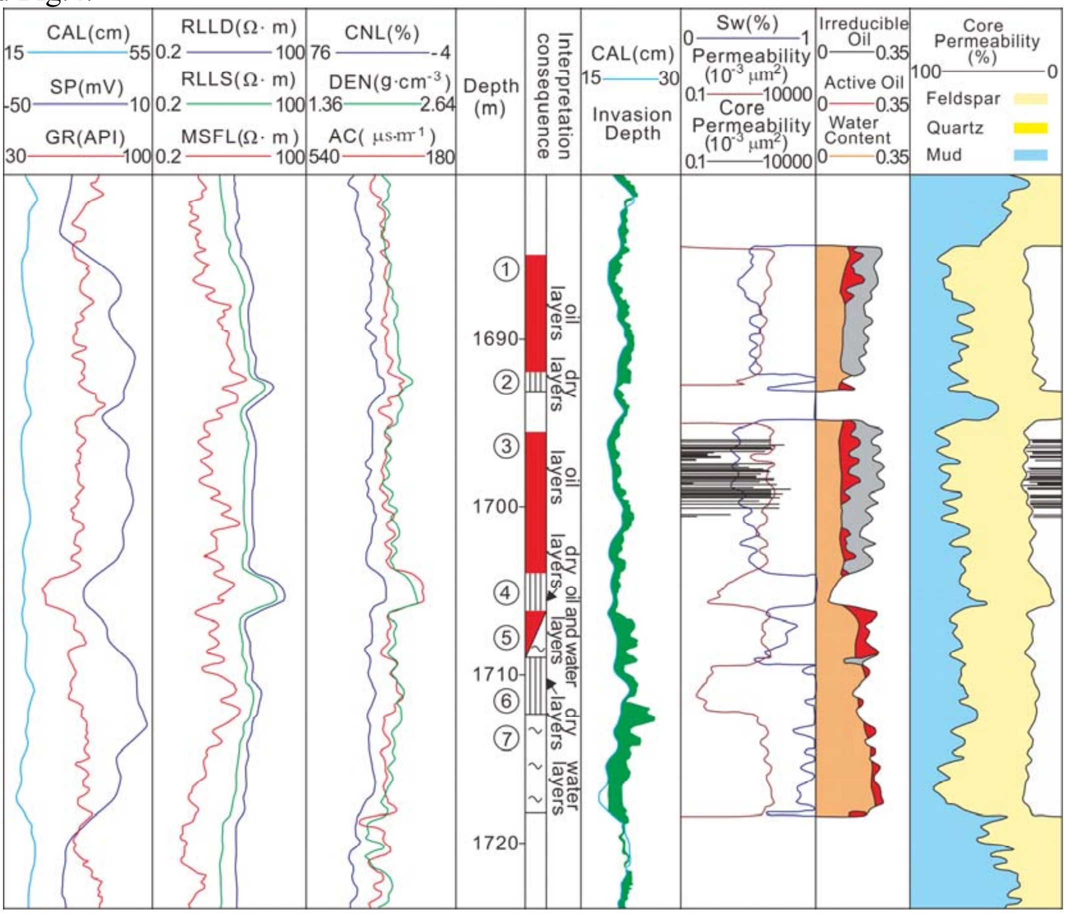

Fig.2 Log interpretation of well A1 in A area

Fig.3 and Fig.4 indicate that there is a good correlation between the results of core analysis and multi-mineral log interpretation (the porosity correlation coefficient is 0.88, and the average error is 4.27%; the permeability correlation coefficient is 0.79, and the average error is 10.07%). Besides, the error range is applicable in the study area, and other cored wells also show a good match between the core analysis and multi-mineral log interpretation, indicating that the multi-mineral log interpretation method is advisable and applicable in the study area.

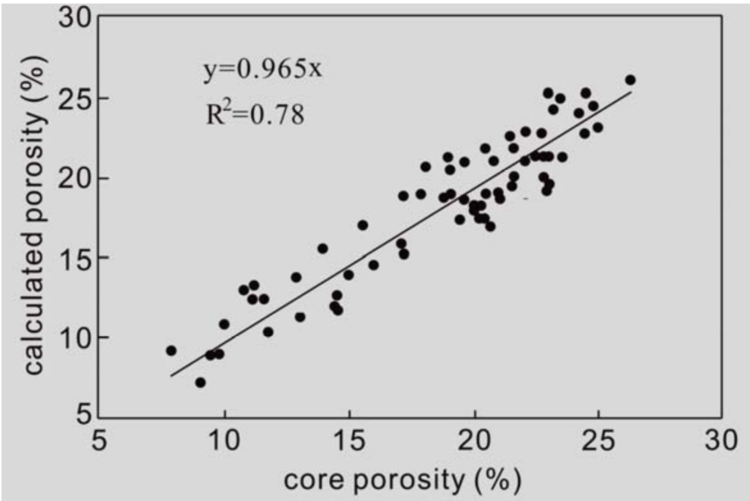

Fig.3 Collation map of core porosity and calculated porosity

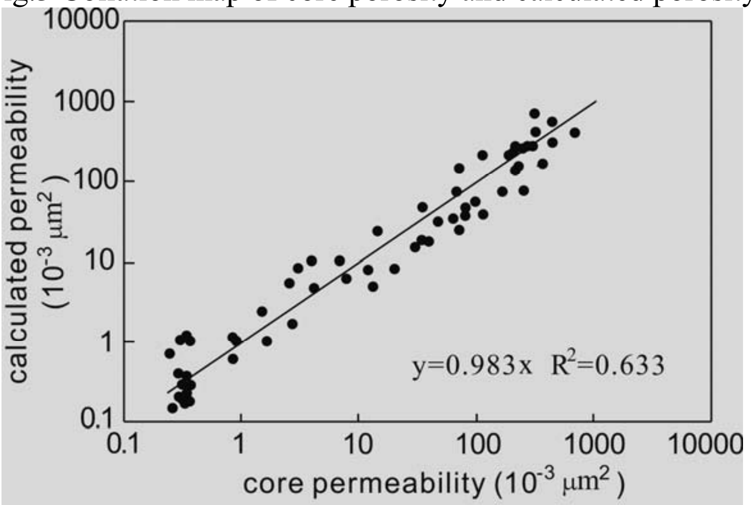

Fig.4 Collation map of core permeability and calculated permeability

5. Conclusions

(1) The unconsolidated sandstone heavy oil reservoirs in A area is evaluated by the optimized methods of multi-mineral model and Scheidger permeability formula, and the computed values and variable tendency of porosity and permeability coincide well with the actual core data.

(2) The optimized method provides dependable models of lithology identification and methods of porosity calculation for accurate interpretation of heavy oil reservoirs, and provides a new clue and approach for the logging evaluation of lithology complex reservoir by conventional log data.

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