Study on interpretation method of remaining oil saturation based on PSSL logging

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Abstract: *Due to the dispersion of residual oil caused by long-term water injection development in oilfields, in order to improve remaining oil recovery, it is necessary to find out the distribution of oil and water and determine the remaining oil enrichment area. In this paper, the logging interpretation principle of Pulsed Neutron Full-Spectra Saturation Logging (PSSL) instrument is introduced. Then, the main formation factors affecting PSSL logging are analyzed, and in the C/O measurement model, a new interpretation model is proposed that uses C/O and Si/Ca to calculate the oil and water lines, and subsequently utilizes the difference between the measured C/O and the oil and water lines to explain the water flooding. By establishing the cross plot of the difference between the measured C/O and the oil and water lines, the influence of lithology and petrophysical properties on the measured value can be reduced to a certain extent, and the flooded layer can be accurately and quickly identified. This method provides technical guarantee for determining the distribution of oil and water in the oilfield, evaluating the level of flooding, and taking measures to block water and re-perforation.*

Keywords: *PSSL; Carbon-to-oxygen ratio; Remaining oil saturation; Identification of water flooded layers*

1. Introduction

With the continuous development of reservoir water injection, most reservoirs have been flooded to varying degrees, and the distribution of reservoir water content is disordered. Different water content leads to more complicated underground oil-water relationship[1]. In order to increase oil reserves and increase oil production, it is necessary to tap the potential of old oil fields. It is very important to distinguish oil-water layers, accurately find potential layers and master the distribution law of remaining oil.

At the later stage of development, the original state of reservoir has changed greatly, and the salinity and resistivity of formation water are difficult to determine, which affects the accuracy of logging interpretation. However, conventional neutron lifetime logging cannot be used in low salinity formations, and electrical logging cannot be used in formation evaluation of cased wells. Therefore, PSSL logging is introduced, which can not only identify the watered-out layer in the strata with low salinity, unknown salinity or large salinity change, but also determine the remaining oil saturation in cased wells, and is an important method for oilfield dynamic monitoring and optimization of potential tapping measures. PSSL logging integrates carbon-oxygen ratio, neutron lifetime and oxygen activation logging, and multiple logging curves in various modes support each other, eliminating multiple solutions, greatly improving the coincidence rate and accuracy of measurement, and having strong applicability. In recent years, C/O logging plays a very important role in identifying water-flooded zones and determining the remaining oil saturation[2]. At present, the common method used in the measurement mode of C/O ratio is to identify water-flooded zones by overlapping the measurement curves of C/O ratio and Si/Ca ratio, and to identify water-flooded zones by using the cross-plot of C/O ratio and Si/Ca ratio. However, when the lithology of local zones changes, the identification effect is poor. Based on the interpretation model of carbon-oxygen specific energy spectrum, this paper uses the intersection method of oil line difference and water line difference to quickly identify watered-out layers, and obtains good application results.

2. Principle of pulsed neutron spectroscopy logging

In the monitoring of remaining oil in cased wells, pulsed neutron spectroscopy logging is one of the

best methods to determine the remaining oil saturation at present. Its advantage is that it can directly detect the formation without being affected by the media such as instrument shell, well fluid and casing, and the measurement results are not affected by the salinity of formation water[3]. In this method, 14.1Mev pulsed neutrons generated by neutron accelerator bombard the formation, and react with the nuclei of carbon, hydrogen, oxygen, silicon, calcium and other elements in the formation in turn, such as inelastic scattering, elastic scattering, radiation capture and oxygen activation[4]. Gamma rays with different intensities and energies are generated, and inelastic scattering gamma spectrum, captured gamma spectrum, inelastic-captured gamma time spectrum, thermal neutron captured gamma time spectrum and activation energy spectrum are recorded respectively according to time and energy[5]. Different energy spectra can be extracted by choosing appropriate "energy window", and the distribution of these energy spectra reflects the relative yield of formation elements, so as to determine the lithology, physical properties, oil-bearing and other information of the formation.

Carbon-oxygen ratio logging, as an important method of PSSL logging, mainly occurs in the inelastic scattering stage within $10^{-8} \sim 10^{-7}$s after fast neutron emission. High-energy pulsed neutrons react with the nuclei of formation elements to produce gamma rays with different energy and characteristic peaks, so as to reflect the relative yield of formation elements. According to the content law of elements in the formation: there is more carbon in oil and gas and more oxygen in formation water, so C and O are used as indicator elements of oil, gas and water in the formation; There are many silicon elements in sandstone and many calcium elements in carbonate rocks, so Si and Ca are used as indicator elements of formation lithology. Generally speaking, a high Si/Ca ratio corresponds to a sandstone layer, while a high C/O ratio and a high Si/Ca ratio generally correspond to an oil layer. The ratio method can not only characterize the oil-water information of the formation, but also eliminate the influence of unstable neutron yield and background noise during instrument measurement[6].

3. Analysis and correction of influencing factors

3.1. Analysis of influencing factors

In PSSL logging interpretation, the ratio of carbon to oxygen is used to reflect the oil-bearing property of the formation, and the interpretation conclusion is not affected by multiple factors of the formation. The influence of lithology, porosity and oil saturation of forward formation on carbon-oxygen ratio is simulated by Monte Carlo numerical simulation. As shown in Figure 1, the response of C/O ratio changes regularly with the change of lithology, porosity and oil saturation, indicating that C/O ratio is sensitive to lithology, porosity and oil saturation.
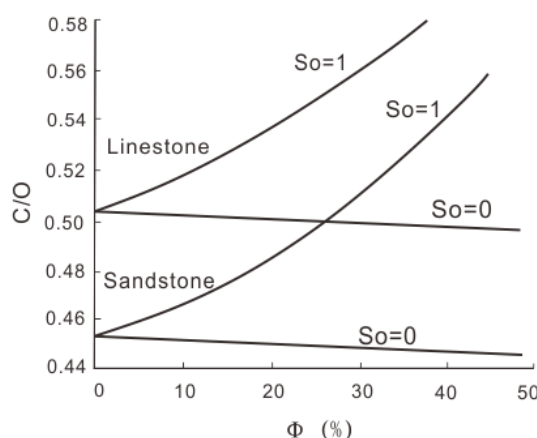

Fig. 1: Relationship curve of C/O ratio with porosity and oil saturation

It can be seen from the simulation in Figure 1 that under the condition of eliminating the influence of lithology and physical properties, that is, in the same porosity of the same formation, the oil saturation is positively correlated with the carbon-oxygen ratio, and So=1 and So=0 are on the upper and lower sides respectively. According to this changing trend, when establishing the oil-water line model, the linear interpolation method can be adopted between the carbon-oxygen ratio of pure water layer and pure oil layer to calculate the oil saturation corresponding to each carbon-oxygen ratio[7].

Without eliminating lithology, that is, for formations with different lithology and the same porosity, the higher the oil saturation, the greater the C/O ratio. However, according to the simulation results in

Figure 1, the change of C/O ratio caused by different oil saturation is obviously smaller than that caused by different lithology (rock skeleton). Therefore, lithology correction must be carried out in the stratum with complex lithology.

Under the condition that the physical properties are not eliminated, that is, for the formations with the same lithology but different physical properties, the C/O ratio decreases with the increase of porosity in the pure water formation with So=0. In the oil-saturated formation with So=1, the C/O ratio increases with the increase of porosity, and the greater the increment of C/O ratio, the higher the sensitivity, indicating that the greater the porosity, the more accurate the oil-water layer division[8].

3.2. Correction of influencing factors

When using the measured carbon-oxygen ratio to identify formation fluid, because carbon and oxygen elements are influenced by formation rock skeleton and formation water, it is impossible to distinguish whether the measured total carbon content comes from oil and gas or formation skeleton, and whether the total oxygen content comes from formation water or formation skeleton, and generally speaking, it is impossible to only come from one of them. When the formation skeleton contains carbonate composition, the carbon content in the formation increases, and the measured value of carbon-oxygen ratio increases with the increase of carbonate composition. When the shale of the formation skeleton contains organic matter, the carbon content in the formation increases, and the measured carbon-oxygen ratio increases with the increase of shale content. If the shale only contains bound water, the oxygen content in the formation increases, and the measured value decreases with the increase of shale[9].

Si/Ca ratio changes little with porosity and greatly with lithology. If the influence of lithology change on measured values is not considered, the interpretation conclusion will be biased. Therefore, in order to avoid the influence of carbon content in carbonate skeleton, the ratio of silicon to calcium is usually used to correct lithology, and the isoline between the two lithology reflects the change of calcium content. The calculation formula (1) of calcium content is as follows:

$$V(CO_3) = \frac{(Ca / Si)_{\log} - (Ca / Si)_{pure\ stratum}}{\delta(Ca / Si)} \tag{1}$$

In the formula: $V(CO_3)$ is the calcium content. $(Ca / Si)_{\log}$ is the Ca/Si ratio of the target layer; $(Ca / Si)_{pure\ stratum}$ is the Ca/Si ratio of pure sandstone layer. $\delta(Ca / Si)$ is the difference of Ca/Si ratio between pure limestone and pure sandstone.

In order to avoid the influence of organic matter in the mud on the interpretation conclusion, the rock volume model is usually used for mud correction of C/O and Si/Ca, such as formulas (2) and (3).

$$(C / O)_C = \frac{(C / O)_{\log} - V_{sh}(C / O)_{sh}}{1 - V_{sh}} \tag{2}$$

$$(Si / Ca)_C = \frac{(Si / Ca)_{\log} - V_{sh}(Si / Ca)_{sh}}{1 - V_{sh}} \tag{3}$$

In the formula: $(C / O)_C, (Si / Ca)_C$ are the corrected carbon-oxygen ratio and silicon-calcium ratio respectively. $(C / O)_{\log}, (Si / Ca)_{\log}$ are the measured values of carbon-oxygen ratio and silicon-calcium ratio respectively. V_{sh} is the shale content of the formation. $(C / O)_{sh}$ and $(Si / Ca)_{sh}$ are the shale carbon-oxygen ratio and silicon-calcium ratio respectively.

4. Establish an interpretation model and method

4.1. Establish an interpretation model

Oil saturation is an important parameter in PSSL logging interpretation. When using PSSL logging to calculate oil saturation, predecessors have done a lot of research and innovation, but all of them have their applicability and limitations. ① Simple linear interpretation method: the premise of adopting this method is to keep the porosity and lithology unchanged, which is difficult to guarantee in practical application; ② C/O and capture Si/Ca intersection method: oil saturation is calculated on the basis of

lithology and physical properties correction, but it is difficult to completely correct general lithology and physical properties, and the slope and intercept of oil line and waterline are sometimes difficult to determine; ③ The method of combining theoretical derivation with simulated well calibration data: it is difficult to meet the requirements in practical application under the assumption that the formation skeleton and formation water do not contain carbon; ④ Hertzog model: The fitting value in the calculation formula model indicates the contribution proportion of carbon and oxygen in the borehole to the measured carbon and oxygen, which is only related to borehole fluid and borehole size. If the borehole size and borehole fluid are known, the fitting value is constant, but in most cases, the borehole fluid is unknown or changing.

On the basis of comprehensive analysis of the above models, the intersection method of C/O and Si/Ca is preferred to calculate the remaining oil saturation. First of all, it is necessary to calculate the pure water line of the measuring well section, select the water section with pure lithology, no calcium and low mud content, draw the cross diagram of C/O and Si/Ca, and find out the best water line; Secondly, the waterline is subtracted from the measured value of C/O ratio to get the increment $\triangle$(C/O) between the waterline and the measured value of C/O ratio, which has nothing to do with formation lithology. Then the normalized interpretation chart is established by using the linear interpolation formula of oil saturation, and finally the established chart is used to fit the oil saturation interpretation model.

Calculate the oil saturation by the intersection of C/O and Si/Ca, as shown in Formula (4):

$$S_o^b = \frac{C/O + K_w \cdot Si/Ca - L_w}{a\phi^b} \tag{4}$$

In the formula: S_o^b is the oil saturation of the formation. ϕ is the formation porosity. C/O is the measured value of carbon-oxygen ratio, dimensionless. Si/Ca is the measured value of captured silicon-calcium ratio, dimensionless. K_w, L_w are the slope and intercept of cross plot between C/O and Si/Ca in water layer. a and b are constant, and usually a takes 0.6 and b takes 1.11[10].

When calculating the model waterline, the data of pure water layer are selected for C/O and Si/Ca intersection. Figure 2 is the intersection diagram of C/O and Si/Ca drawn by Atlas. It can be seen from the figure that even in strata with different lithology, the waterline points basically fall near the same straight line, and the connecting lines of the oil waterline points form many straight lines parallel to the waterline. With the increase of porosity, the distance between the oil waterline and the waterline also increases. When the oil saturation in formula (4) is So=0, the waterline can be linearly expressed by formula (5) as follows:

$$(C/O)_{w100} = a(Si/Ca) + b \tag{5}$$

In the formula, a is the slope of the waterline. b is the intercept of the waterline on the C/O axis. $(C/O)_{w100}$ is the waterline value. Si/Ca is the corrected silicon-calcium ratio. Due to the influence of formation environment factors in different areas, the slope a and intercept b of waterline need to be reconfirmed. Fig. 3 is a cross plot of C/O and Si/Ca of pure water layer measurement in Fal block. The waterline equation of Fal block is obtained through calculation, as shown in Formula (6):

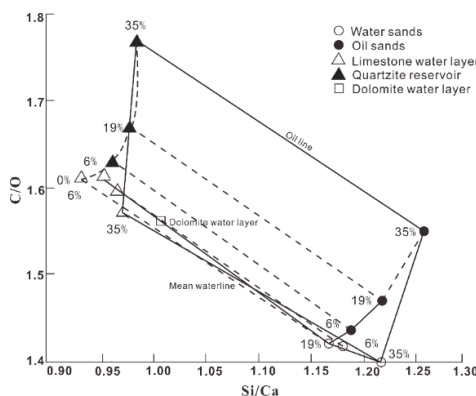$$(C/O)_{w100} = -0.525(Si/Ca) + 1.301 \tag{6}$$
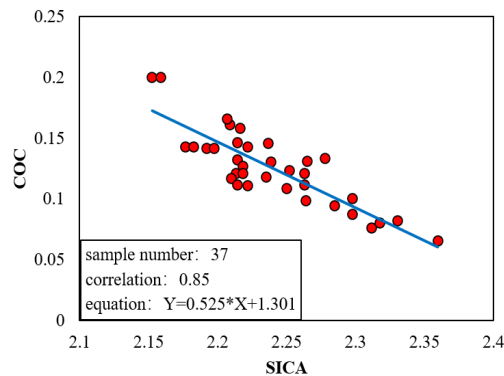

Fig. 2: Oil-water envelope

Fig. 3: The cross-plot of C/O and Si/Ca

4.2. Interpretation method

When PSSL logging method is used to process the data and make the interpretation chart of watered-out layer, the conventional method is to identify oil-water layer by using the cross plot of carbon-oxygen ratio and silicon-calcium ratio. In this block, it is found that different watered-out layers can be distinguished after lithologic correction when using the cross-plot of C/O ratio and Si/Ca ratio. However, according to the on-site perforation and oil production, there is a deviation between the production and the interpretation conclusion, which fails to reach the expected production. The analysis may be due to the incomplete lithologic correction of the formation.

By observing the response characteristic curve of C/O ratio logging in well X26 in Figure 4, it is found that the measured value of C/O ratio, oil line and water line in the fifth channel have obvious regular changes. The measured value of C/O ratio of No.1 layer almost coincides with the oil line, showing the phenomenon of double peaks in the same direction, which is far from the water line. Combined with other corresponding intervals, it is comprehensively interpreted as an oil layer. The measured values of C/O ratio of Layer 2 and Layer 3 almost coincide with the waterline, and the phenomenon of double valleys in the same direction appears, which is far from the oil line. This interval is comprehensively interpreted as a water layer. It is found that the distance between the measured value of carbon-oxygen ratio and the oil line and water line can be used as an important basis for dividing oil-water layers.
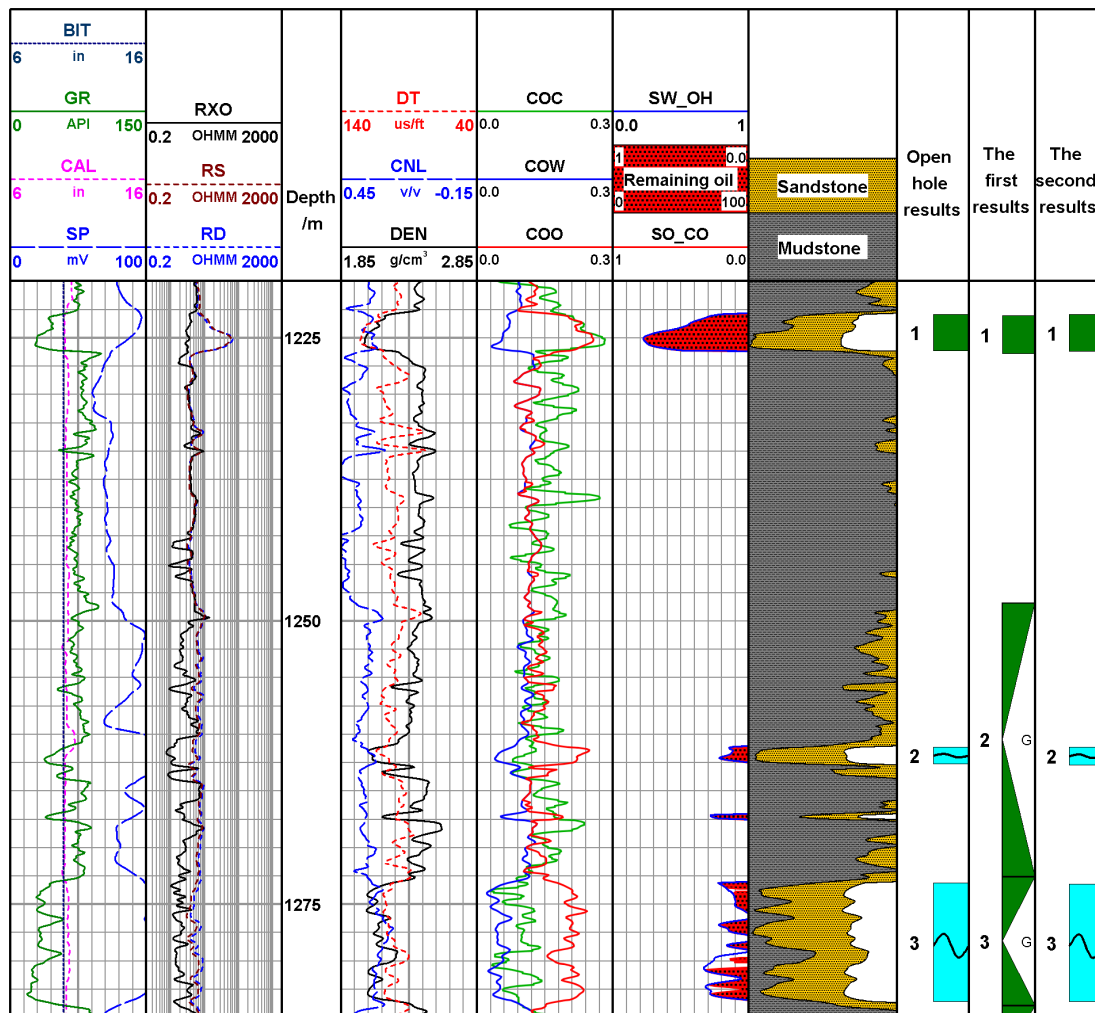

Fig. 4: Logging response characteristics of typical oil-water layers in Well X26

It is found that the distance between the measured value of carbon-oxygen ratio and the oil line and water line can be used as an important basis for dividing oil-water layers. Therefore, this paper establishes the models of oil line and waterline according to the C/O ratio and Si/Ca ratio measured by PSSL, and uses interpolation method, oil line and waterline to construct the intersection diagram of waterline difference and waterline difference to identify the flooded layer qualitatively. The identification diagram

is shown in Figure 5, and the criteria for judging each flooded level are shown in Table 1.

The water flooded layer is identified by the intersection diagram method of waterline difference and oil line difference (C/O-COW and COO-C/O). The two dotted lines represent the dividing lines of high water flooded layer, medium water flooded layer and low water flooded layer from top to bottom, which can distinguish the water flooded level intuitively. The advantage of this method is that the measured value of C/O ratio is subtracted from the waterline value on the X axis, and the measured value of C/O ratio is subtracted from the oil line value on the Y axis, and the relative value is used for intersection. If the measured value is not completely corrected, the oil line and water line are obtained on this basis with the same error. If the difference method is used to subtract the same error, the influence of incomplete correction of lithology can be avoided and the interpretation conclusion can be more accurate.
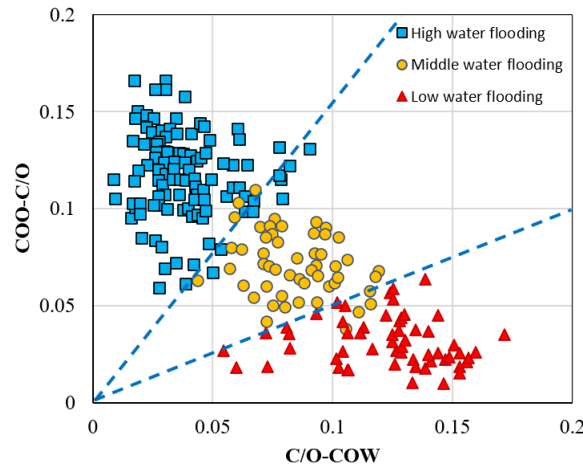

Fig. 5: qualitative identification chart of water flooded level in PSSL logging

Table 1: Criteria for judging flooding level of PSSL logging

Flooding grade	Discriminant relation
Low water flooding	(COO-C/O) < 0.4914* (C/O-COW)
Middle water flooding	(COO-C/O) > 0.4914* (C/O-COW) (COO-C/O) < 1.5833* (C/O-COW)
High water flooding	(COO-C/O) > 1.5833* (C/O-COW)

5. Field application

Fig. 6 Well X28 was put into production in March 2012, with an initial oil production of 1377 barrels per day and a water cut of 1.3%. A logging interpretation was conducted in 2016, and a second logging interpretation was conducted by PSSL in October 2020. As shown in Figure 6, the PSSL logging interpretation results show that the measured value of C/O ratio of Layer 1 (interval from 1305.1 to 1306.8 m) is consistent with the oil line height, far from the waterline, which is a typical oil layer feature. After perforation of Layer 1, the daily oil production is 321 barrels per day and the water production rate is 2.37%, indicating that Layer 1 is consistent with the interpretation conclusion. No.2 layer (1347.51~1356.4m) was interpreted as an oil layer, and once as a highly watered-out layer. According to the measured value of C/O ratio, it decreased in the same direction as the waterline, and was extremely close to the waterline, far below the waterline. The second interpretation was highly watered-out. After the measures, the upper part of No.2 layer was perforated for trial production, and the daily oil production was 155 barrels per day, the daily water production was 673 barrels per day, and the water cut was 81. No.3 layer (1398~1408.1m) has good physical properties, the measured value of C/O ratio coincides with the waterline, and there is a phenomenon of double valleys in the same direction, which is far from the oil line. The three comprehensive interpretations are all water layers, and no measures have been taken.
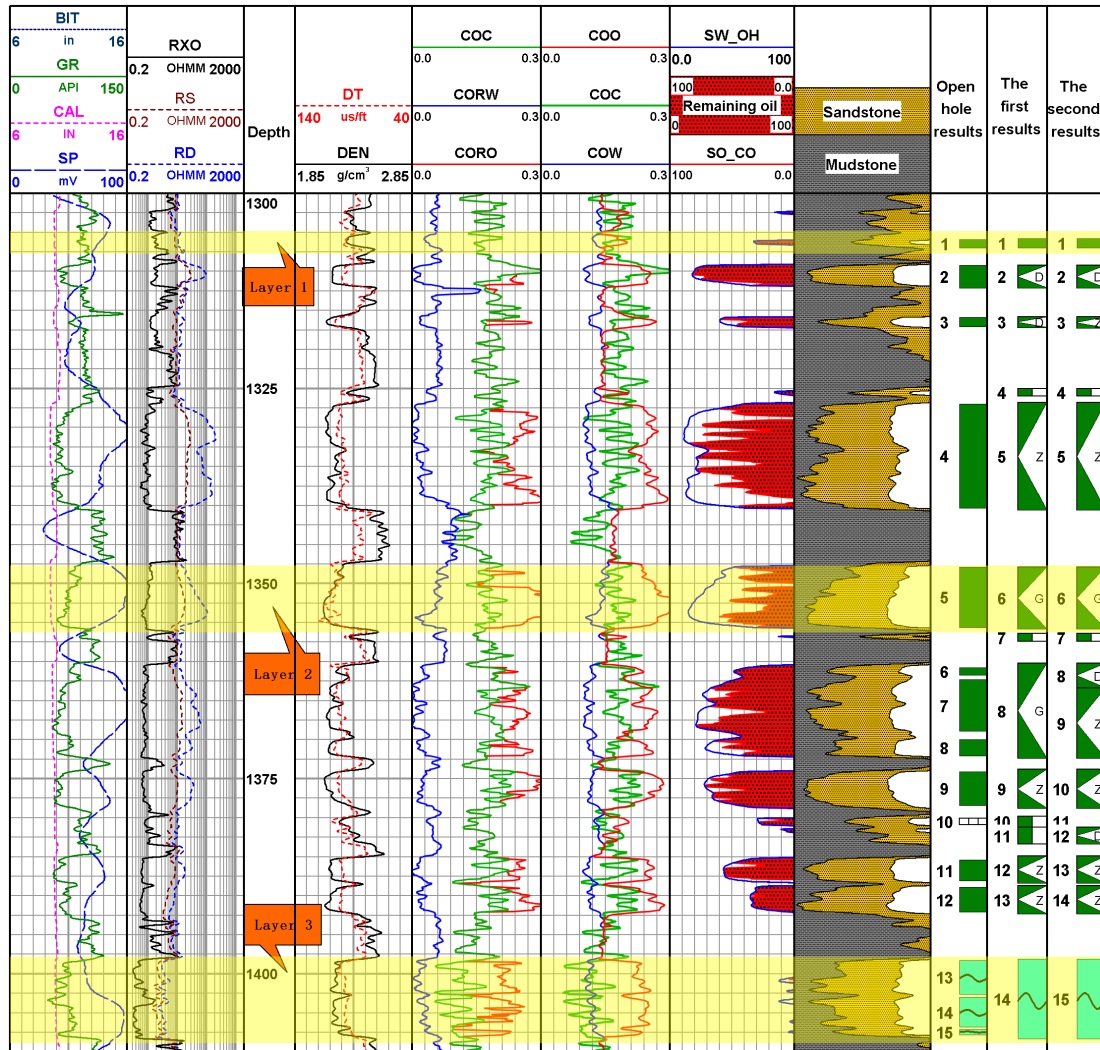
Fig. 6: Well X28 PSSL logging interpretation result chart

In order to study the application of the method, 33 wells in PSSL were treated in combination with the effectiveness of measures and the production performance curve, and the coincidence rate of qualitative interpretation was counted, and 30 wells were consistent and 3 wells were inconsistent, with the coincidence rate reaching 90.9%.

6. Conclusions

(1) Pulsed neutron spectroscopy logging is different from the single logging method in the past. It integrates multiple measurement modes and measures multiple logging curves at one time, which can realize the comprehensive interpretation of static and dynamic data, data before and after casing, open hole and regional geological data, and is more accurate in the evaluation of remaining oil in the oilfield and the identification of oil-water layers.

(2) When using C/O logging to identify the flooded layer, the oil line difference and water line difference intersection diagram are used to make an interpretation chart to identify the flooded layer qualitatively. This method uses relative difference to eliminate the influence of lithology and physical properties, which can quickly and intuitively explain the flooded layer and has good application effect.

(3) The new method of identifying water-flooded zone with C/O ratio in pulsed neutron energy spectrum logging mode eliminates the influence of multiple factors in formation, and plays an important role in fine division of oil-water zone, identification of water-flooded zone and adjustment of production measures.

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