Methods of Calculating Total Organic Carbon from Well Logs and its Application on Rock's Properties Analysis*

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Abstract

The total organic carbon content (TOC) is a crucial indicator for the evaluation of shale gas reservoirs, traditionally estimated by measuring cores, cuttings or sidewall cores in laboratory with source rock evaluation instruments. Limited by the number of rock samples, the experimental results are not continuous and it is impossible to show the whole face of a source rock bed. Continuous high resolution logging information contributes to overcoming the restraints mentioned above. In this paper, the measured TOC data obtained from geochemical analysis of the core samples has a low correlation with any single logging curve from a shale gas well in southern China. The TOC calculated from the commonly used method ΔlogR technique has a relatively low correlation with the measured ones, especially in the interval of low TOC. Three methods of ΔlogR technique, optimal superposition coefficient ΔlogR technique, CARBOLOG (Carbon Organic LOG) technique are applied to calculate TOC and compared. Calculated results show that TOC from CARBOLOG technique is better related to the measured TOC with the correlation coefficient for 0.83. Based on the calculated TOC from CARBOLOG technique, analysis of TOC effects on rock properties is performed, showing the characteristics of high S-wave Impendence (SI), high Poisson's ratio (ν), high Vp/Vs ratio (VpVs) with high TOC, which is consistent well with the forward modeling results using the 3D SCA_DEM rock physics model for organic-rich shale.

Introduction

As we all know, shale gas reservoirs are a kind of self-generated and self-stored reservoirs. Relative to non-hydrocarbon source rocks, shale gas reservoirs have a definite difference in well logging response due to the unique physical properties of organic matter, showing the characteristics of high acoustic transit time, high resistivity, high gamma ray and low density. As a result, integrated with certain techniques, using the different well logging response between non-hydrocarbon source rocks and hydrocarbon source rocks to identify and calculate TOC (Total Organic Content) is available. This paper employs ΔlogR technique, optimal superposition coefficient ΔlogR technique, CARBOLOG (Carbon Organic LOG) technique respectively to calculate TOC. Calculated results show that CARBOLOG technique is consistent better with those measured from chemical analysis than the other methods. Based on the calculated results from CARBOLOG technique, we discuss the

TOC effects on rock properties with crossplots of different elastic parameters. Compared with the forward modeling by the 3D SCA_DEM rock physics model for organic-rich shale, significant inclusions has been obtained.

Theory

ΔlogR technique was proposed by EXXON and ESSO (Passey et al., 1990) which employs the overlaying of porosity logs (sonic, density, neutron) in arithmetic coordinate and resistivity log in logarithmic coordinate with fixed superposition coefficient to identify and calculate TOC. With the appropriate baseline, we can calculate the ΔlogR distribution to establish the quantitative interpretation relationship between TOC and ΔlogR. The algebraic expression that was used by Passey for the calculation of ΔlogR from the sonic/resistivity is:

$$\Delta\log R = \log R/R_{baseline} + 0.0061(\Delta t - \Delta t_{baseline}) \quad (1)$$

Where ΔlogR is the curve separation between porosity log and resistivity log; R is the resistivity measured in Ωm; Δt is the transit time measure in us/m; $R_{baseline}$ is the resistivity corresponding to the $\Delta t_{baseline}$ when the curves are baseline in non-source rocks. Passey used the following empirical equation to calculate TOC in source rocks from ΔlogR:

$$TOC = \Delta\log R \times 10^{(2.297-0.168LOM)} + \Delta TOC \quad (2)$$

Where LOM is the amount of level organic metamorphism and ΔTOC is regional background level.

However, ΔlogR technique needs selecting baseline artificially, which is relatively complicated with strong subjectivity. In addition, TOC background level is different regionally and not easy to determine. The method is restricted in the area lack of LOM. In order to solve the problem, Liuchao (2011) proposed improved ΔlogR technique called optimal superposition coefficient ΔlogR technique, which does not need to determine baseline and calculates TOC directly. He proved that fixed superposition coefficient 0.0061 would affect the accuracy of the calculated TOC and illustrated the physical significance of superposition coefficient. The improved algebraic expression is:

$$TOC = a\log R + b\Delta t + c \quad (3)$$

Where a, b, c are constant coefficients.

The CARBOLOG method (France Petroleum Institute, 1988) assumed that the resistivity of rock frame and organic matter is infinite. We project the four client-side materials of rock frame, clay, water, organic matter onto $R^{-1/2}$ - ΔT plane as shown in Figure 1a. Here the slope of the line connecting rock frame PM (100%) and clay PA (100%) is very close to the slope of the line connecting rock frame PM (100%) and water PE (100%). $R^{-1/2}$ is linearly related to ΔT where the organic matter is equal. Its slope equals to the slope of the line connecting rock frame PM (100%) and clay PA (100%).According to the corresponding logging response of rock composition, Figure 1a is converted to Figure 1b. The line connecting rock frame PM (100%) and water PE (100%) means non-organic matter in Figure 1b. ΔTOM is equivalent to pure organic matter point. For the investment point Mk of each group (ΔT, $R^{-1/2}$) in Figure 1b, drawing a straight line paralleled to I (0%) over point Mk intersected to horizontal axis, and the point of intersection is the volume fraction of organic matter. CARBOLOG technique needs to know at least three client-side materials and the chart is easy to understand but difficult to calculate TOC. To solve the problem, Liu (2008) derived the following expression:

$$TOC = a\Delta t + bR\text{-}1/2 + c \qquad (4)$$

Where a, b, c are constant coefficients.

Application

Integrating with the measured TOC obtained from a shale gas well in the south of China, we establish the crossplots of acoustic transit time (AC) versus measured TOC, density (DEN) versus measured TOC, Gamma ray (GR) versus measured TOC with the correlation coefficient as 0.2641, 0.2031, 0.1408 respectively as shown in Figure 2a-c. Any single logging curve is not well related to the measured TOC.

The ΔlogR technique, optimal superposition coefficient ΔlogR technique, and CARBOLOG technique are applied respectively to calculate the TOC. The Figure 3 illustrates that the TOC calculated from all the three methods have a good agreement with the measured TOC except ΔlogR due to the failure of selected baseline. However, the computed value is lower than the measured TOC especially in the interval of high TOC. Comparing the calculated results from the three methods, we can find that CARBOLOG technique works better, especially in the interval range from 585 to 600 meters.

Figure 4 shows the crossplots between the calculated TOC using the three methods and the measured TOC. The linear correlation coefficient is 0.62 between the calculated TOC for ΔlogR technique and the measured TOC. In terms of optimal superposition coefficient ΔlogR technique, the related degree is 0.79. In comparison with the other two methods, CARBOLOG technique gets results better related to the measured TOC with the correlation coefficient for 0.83. When the TOC is high, CARBOLOG technique works better.

Figure 5 shows schematic view of 3D SCA_DEM rock physics model for organic-rich shale which incorporates Budiansky-Hill’s SCA model (Budiansky, 1965), Norris-Berryman’s DEM model, Berryman’s 3D special pores, Biot-Gassmann’s equation (Biot, 1956), and Brown-Korringa’s equation (Brown and Korringa, 1975). The recipe of rock physics modeling is as the followings:

(1) Calculating the bulk modulus (Kdry) and shear modulus (μdry) of dry rock using the combination of SCA and DEM model. There are two kinds of calculation algorithms for the pore factors (P and Q). One is Wu’s arbitrary pore aspect ratio, and the other is Berryman’s 3D special pores;
(2) Calculating the bulk modulus (Ksat) and shear modulus (μsat) of saturated rocks using Biot-Gassmann’s equation;
(3) Calculating the effective modulus with the solid substitution of TOC using Brown-Korringa’s equation.

Aimed at an organic-rich shale composed of clay-quartz mineralogy with porosity of 15% and water saturation of 100% (K_{clay}=17GPa, μ_{clay}=8GPa, K_{quartz}=36GPa, μ_{quartz}=44GPa). Figure 6 shows the forward modeling result of cross-plots between geological and geophysical properties for the spherical pores, which illustrates that with the increasing clay content, the TOC effects might be different. That means the TOC effects depend on the clay content.

Figure 7 illustrates crossplots of different elastic parameters between high TOC (>2%, depicted by pink points) and low TOC (<2% depicted by blue points). We can clearly see the effects of TOC on different rock properties, showing the characteristics of high S-wave Impendence (SI), high Poisson's ratio (ν), high Vp/Vs ratio (VpVs), low μρ, which is consistent well with the forward modeling results by the 3D SCA_DEM rock physics model.

Conclusions

In order to calculate the TOC precisely, three methods have been applied in this paper. Based on the TOC amounts calculated by CARBOLOG technique, analysis has been performed to obtain the effects of TOC on the elastic parameters of organic-rich shale. Argumentation and analysis conclude:

(1) ΔlogR technique does not work very well possibly due to the failure of selected baseline. Calculated TOC by the other two methods employed in this paper has a good agreement with the measured TOC in the variation trend.
(2) Relative to the other methods, CARBOLOG technique gets calculated results better related to the measured TOC from chemical analysis, especially in the interval of low TOC.
(3) Forward modeling results by the 3D SCA_DEM rock physics model shows the characteristics of high S-wave Impendence (SI), high Poisson's ratio (ν), high Vp/Vs ratio (VpVs) and low μρ with low TOC.
(4) Based on the calculated TOC from CARBOLOG technique, crossplots of different elastic parameters has been obtained, still showing the characteristics of high S-wave Impendence (SI), high Poisson's ratio (ν), high Vp/Vs ratio (VpVs) and low μρ with low TOC. The observation from measured TOC is consistent well with the forward modeling results by 3D SCA_DEM rock physics model.

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