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Implementing Direct and Indirect Wireline Methods in Determination of Total Organic Carbon: A Case Study from a West African Hydrocarbon Field

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Abstract

Since the development bloom in unconventional reservoirs in North America, total organic carbon (TOC) has become a more essential parameter, as the indicator of the efficiency of these reservoirs. In this paper, by using conventional well logs and NMR log data, the TOC content of an unconventional reservoir in West Africa is estimated. Passy's, Issler's, and Schmoker's methods were used as indirect wireline methods to estimate TOC content, along the well paths. Afterward, NMR log data, as a direct method, was used to provide more precise calculations of TOC. Both methods showed almost similar trends, with the NMR method indicating lower values for the TOC. Then, an adjusted Schmoker equation was proposed, which showed the best fit between NMR and conventional well logs results. By using the equation, the TOC content was calculated in three other wells, where NMR data were unavailable. The results were then used to prepare a 3D model of the TOC distribution, within the reservoir.

Keywords: NMR, TOC, Unconventional Reservoirs, Well Logs, West African

1. Introduction

In the last decade, the prevalence of hydrocarbon production from unconventional reservoirs has increased. North American countries, particularly the United States, have been converting shale and tight formations into their main resources, which is estimated to provide levels of oil production higher than six million barrels per day (Xiong et al., 2019). This is feasible due to advances in both horizontal drilling and multistage hydraulic fracturing, which will enhance the bulk rock permeability (Lee et al., 2011).

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Meanwhile, geochemistry plays a vital role in identifying sweet spots in unconventional resources. However, the organic-rich shales display a wide range of attributes, which makes it a challenge to characterize them (Michael et al., 2017).

1.1. Total organic carbon (TOC)

The organic matter content of a source rock that can be converted into hydrocarbons is known as total organic carbon (Jarvie et al., 2007). It represents a qualitative measurement of source rock potential (Ma and Holditch, 2015). In petroleum industry the TOC and kerogen terms are often used interchangeably, which is incorrect. In an oil-bearing source rock play, TOC is a combination of kerogen, bitumen, and liquid hydrocarbon (Steiner et al., 2016). Kerogen is insoluble in organic solvent due to high molecular weight and comprises a mixture of organic chemical compounds. TOC can be anywhere from very low (lower than 0.5%) to very high (higher than 12%) level of richness (Table 1).

Table 1

Organic content of different source rocks (after Peters, 1986).

Total organic carbon (%)	Kerogen quality
Lower than 0.5	Very Poor
0.5–1	Poor
1–2	Fair
2–4	Good
4–12	Very Good
Higher than 12	Excellent

1.2. TOC Measurement

In order to measure total organic carbon, direct measurements can be taken from cores and drill cuttings using pyrolysis; this method is relatively accurate. However, it is usually associated with higher costs and longer measurement times. Also, the results are noncontinuous measurements as there are limited samples (Alshakhs and Rezaee, 2017).

Continuous wireline logs can be used as an alternative TOC measurement method. There are several equations developed to link the wireline data with the TOC parameter. Wireline methods for TOC measurement can be divided into “direct” and “indirect” categories.

The indirect methods use conventional well logs such as density, neutron porosity, and resistivity logs to predict TOC content (Schmoker and Hester, 1983; Passey et al., 1990; Issler et al., 2002), while NMR log data can be used to calculate the TOC content, as a direct method (Gonzalez et al., 2013). A full description of each method is presented in section 3.

There are also several studies available in the literature, which follow enhanced techniques to measure TOC content. Tabatabaei et al. (2015) hybridized stochastic optimization algorithms with gradient optimization in structure of artificial neural network to estimate TOC from conventional well logs in Ahwaz oilfield. Their input data comprise gamma ray, sonic transit time, compensated neutron, and resistivity logs.

Mahmoud et al. (2017) developed empirical correlation based on conventional well logs and artificial neural networks in order to determine the TOC content of Barnett and Devonian shale formations. Their model showed improved TOC estimation, compared to usual methods.

Xiong et al. (2019) tried to combine cores and well logs together so as to provide a more accurate estimation of total organic carbon. They concluded that in estimation of TOC, there might be more efficient methods in the literature such as machine learning techniques.

In the current study, Passy's, Issler's, and Schmoker's equations are used as indirect wireline methods to estimate TOC in four wells, drilled in one of the West Congo unconventional reservoirs. Afterward, available NMR log data, for one of the wells, is used to directly measure TOC content and provide a coefficient to calibrate the estimated TOC in three other wells. The best linear fit between the indirect methods and NMR method is represented by an adjusted equation, which could provide a continuous TOC measurement along well paths, where NMR is unavailable. Using the adjusted TOC measurement equation provided a continuous measurement of TOC along the four wells, drilled within the reservoir. Then, by using the results, a 3D model of TOC distribution within the reservoir was constructed.

2. Study area

Congo Basin is located in the Western African margin (Figure 1), considered as an early Cretaceous basin where a pre-salt clastic formation exists. It is a large basin, which covers about 1.2×10^6 km^2. The basin also consists of tight sandstone with three layers of marine shale deposited above several intervals in the reservoir (approximately 100 m).

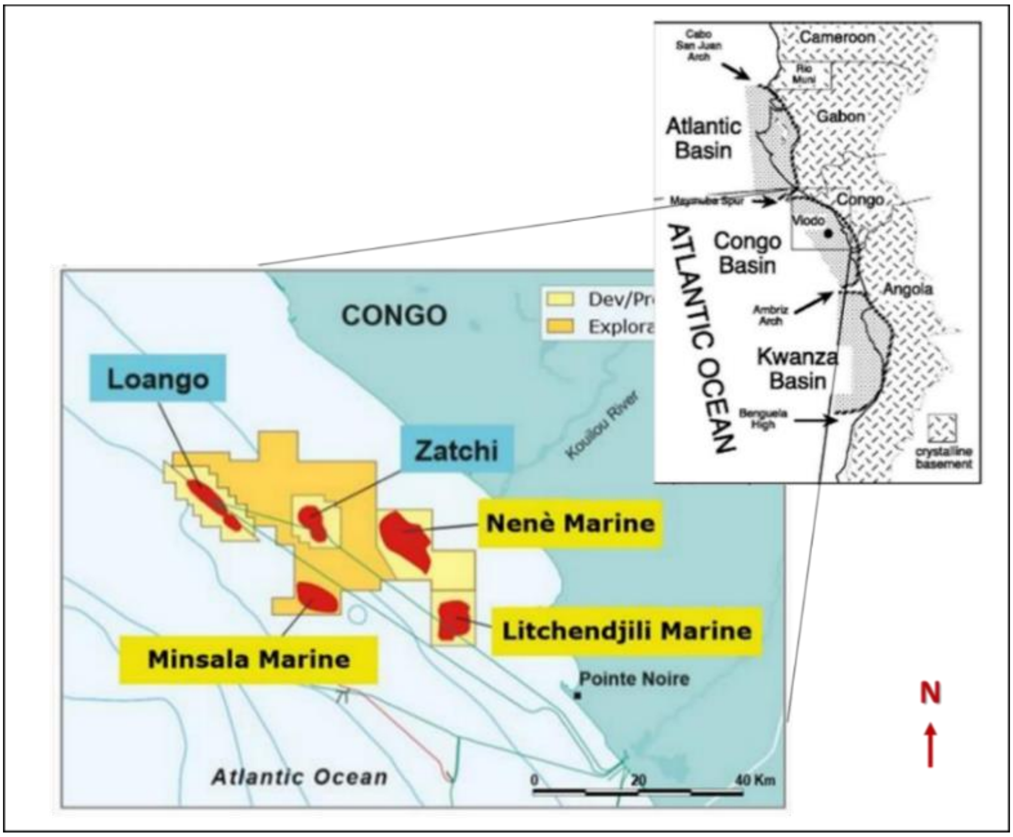


Figure 1

Map showing the approximate location of the studied field.

In the subject field, lithology consists mainly of sandstone, which has been named at the reservoir base as Vandji and at the upper units as Sialivakou and Djeno formations (Figure 2). The Sialivakou comprises grey to black shale and less sandy mudstones, which probably shows a debris flow (Harris, 2000). Djeno formation mainly comprises laminated dark grey shale, with turbidity sandstone intervals.

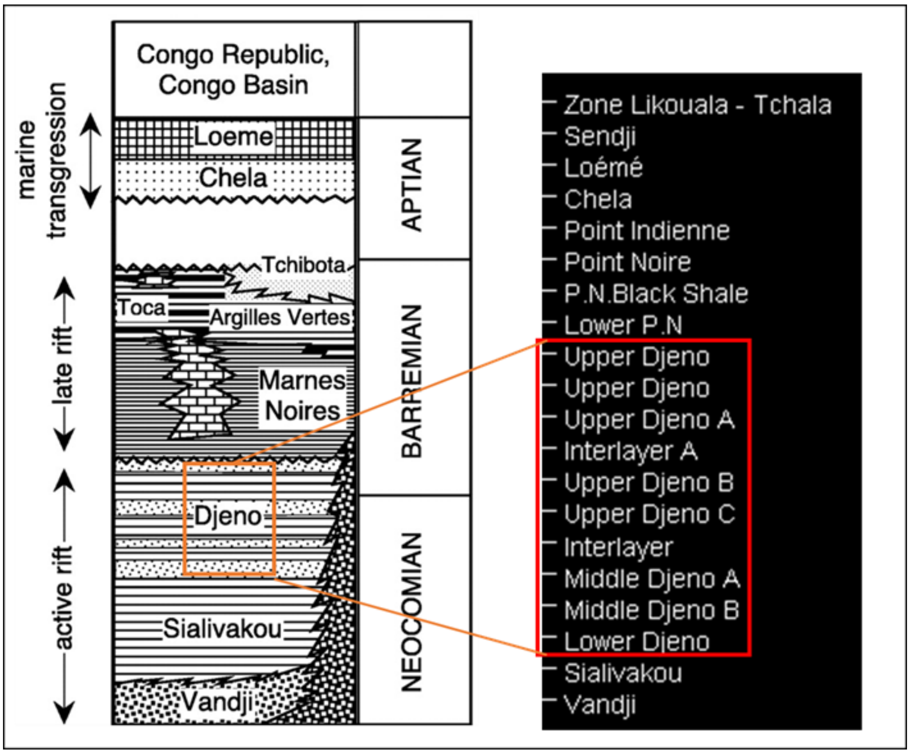


Figure 2
Stratigraphy and observed formations in the studied field.

Harris (2017) suggested that the TOC content of shales in the Congo Basin (lower cretaceous) is an example of interaction between soil development, rift topography, nutrient delivery, and bio-productivity and does not depend on water depth and anoxia. He also reported that through the active rift section, total organic carbon (TOC) averages 2–3%, and kerogen comprises types I and III. In late rift section, TOC averages 6%, which comprises alga and bacterial type I kerogen.

3. Results and discussion

3.1. Indirect wireline methods

Direct and indirect wireline methods measure TOC content continuously along the well path. Table 2 lists the well-known wireline methods that have been introduced for TOC measurement along with their limitations. Measurement with core test methods is limited to both the discrete rock samples and high costs. The used wireline methods are described below.

The Passey's method (ΔlogR) estimates the TOC based on the separation between deep resistivity log (RES) and sonic (DTC), density (RHOB), and neutron (NPHI) well logs due to the presence of organic matter (Passey et al., 1990). Equations 1 to 6 express the relationships available for TOC estimation based on Passey's method.

$$TOC(S) = SF \times Slog_R \times 10^{0.297-0.1688\times LOM} \tag{1}$$

$$Slog_R = log\left(\frac{RES}{RES_{base}}\right) + 0.02 \times (DTC - DTC_{base}) \tag{2}$$

$$TOC(D) = SF \times Dlog_R \times 10^{0.297-0.1688\times LOM} \tag{3}$$

$$Dlog_R = log\left(\frac{RES}{RES_{base}}\right) - 2.5 \times (RHOB - RHOB_{base}) \tag{4}$$

$$TOC(N) = SF \times Nlog_R \times 10^{0.297-0.1688\times LOM} \tag{5}$$

$$Nlog_R = log\left(\frac{RES}{RES_{base}}\right) + 4.0 \times (NPHI - NPHI_{base}) \tag{6}$$

where TOC (S), TOC (D), and TOC (N) represent the total organic carbon obtained from Passey's equations based on sonic, density, neutron well logs respectively. $Slog_R$, $Dlog_R$, and $Nlog_R$ are Passey's numbers from sonic, density, and neutron logs respectively. LOM stands for the level of maturity (considered as 10.5), and SF is scale factor (considered as 0.6).

The TOC calculations from Passey's relationships are illustrated in Figure 3, all of which exhibit a similar trend for TOC content and an average of 2.38. In order to simply compare the results with those of other methods, an average of Passey's three output logs has been created (Figure 4a).

The Schmoker method uses bulk density log (RHOB) and considers the change in formation density as the presence or the absence of low-density organic matter (Schmoker and Hester, 1983). Equation 7 is the proposed formula.

$$TOC_{Schmoker} = \left(\frac{154.497}{DENS}\right) - 57.261 \tag{7}$$

Issler's method is based on the cross-plots of density (DENS) or sonic against resistivity (RES) (Issler et al., 2002; Crain, 2019). The method is defined by the following equation:

$$TOC_{Issler} = SF \times -0.1429 \times \frac{DENS - 1014}{log(RES) + 4.122} + 45.14 \tag{8}$$

where TOC_{Issler} is total organic carbon from Issler's method (weight fraction) and SF represents a scale factor (considered 0.8).

Figure 4a illustrates the calculated TOC from Passey's, Schmoker's, and Issler's methods, which show an average of 2.38, 4.3, and 1.9% respectively.

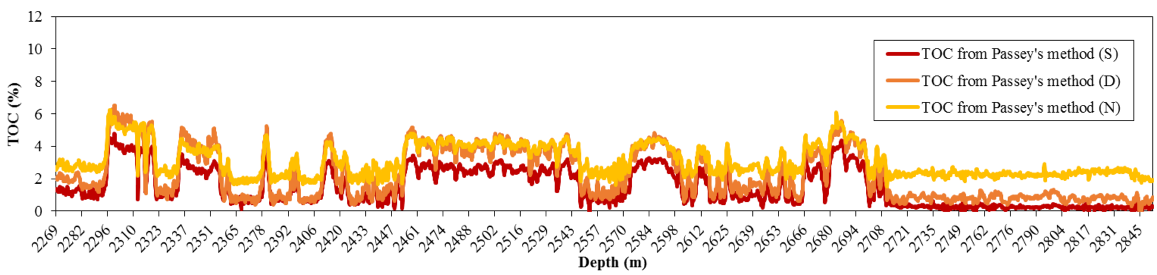


Figure 3

Estimated TOC in well #1 using Passey's method equations.

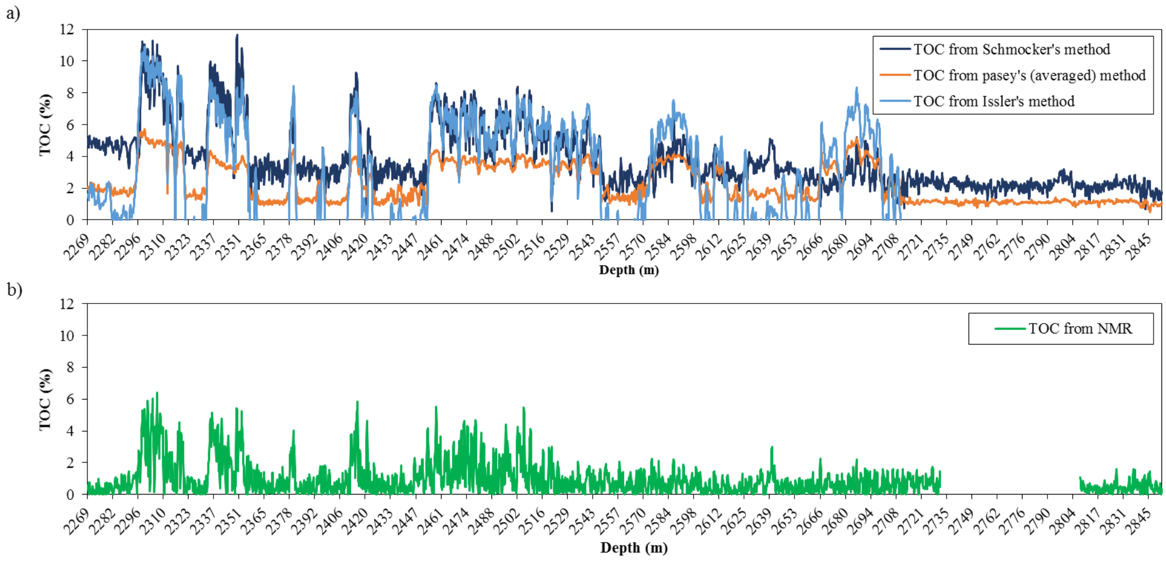


Figure 4

Results of TOC measurement in well #1 using (a) wireline indirect methods and (b) direct NMR method.

Table 2

Limitations of TOC measurement methods using wireline data.

Methods	Limitation	References
Δlog R	Maturity sensitivity; considering same values for baseline and organic-rich depths; clay interference	Passey et al. (2010)
Gross gamma-ray (g)	Reacts mostly to uranium rather than kerogen	Schmoker (1981)
Bulk density	Underestimation of TOC content in clays and carbonates	Schmoker and Hester (1983)

3.2. Direct wireline method

Basically, TOC measurements by direct wireline methods are more precise than the indirect methods. Carbon subtraction, NMR, and pulsed neutron spectral gamma ray are the well-known direct wireline methods (Gonzalez et al., 2013).

An integration of NMR and density log can be utilized in order to measure kerogen volume via the following equation (Gonzales et al., 2013):

$$V_k = \frac{\rho_{mg} - \rho_f}{\rho_{mg} - \rho_k} - \frac{\Phi_{NMR} \times (\rho_{mg} - \rho_f)}{HI_f(\rho_{mg} - \rho_k)} \tag{9}$$

where V_k is the kerogen volume, and ρ_{mg} is apparent matrix density; ρ_k represents kerogen density, and ρ_f stands for pore fluid density; Φ_{NMR} is total NMR porosity, and HI_f denotes the hydrogen index of fluid.

The conversion of kerogen volume into the TOC content can be achieved using the following equation (Tissot and Welte, 1978).

$$TOC = \frac{V_k}{K_{vr}} \times \frac{\rho_k}{\rho_b} \tag{10}$$

where K_{vr} is the kerogen conversion factor and is generally close to 1.2 (Gonzales et al., 2013), and ρ_b is bulk density. Also, by plotting core grain density versus the TOC weight percentage, kerogen density can be obtained.

By applying Equations 9 and 10 and using the values from Table 3, the direct measurement of TOC content for well #1 was performed. Figure 4b illustrates the TOC calculated from NMR method for well #1. The calculated TOC from this method was between 0.0 and 6.4% with an average of 1%.

Due to lack of NMR log in the other three wells of the studied field, we tried to develop a relationship between the calculated TOC from NMR and indirect wireline methods. Comparing the measured TOC from different methods, Schmoker method shows the highest correlation with NMR results with an R^2 of 0.49 (Table 4). Afterward, so as to find the best fit between Schmoker and NMR methods and reduce the mean square error (MSE), the following linear relationship is proposed:

$$TOC_{Adjusted} = (0.46 \times TOC_{Schmoker}) - 0.9 \tag{11}$$

Using the adjusted equation, the MSE in the difference between the calculated TOC from indirect and NMR methods was reduced to 0.58, which was the lowest MSE achieved. Figure 5 illustrates the measured TOC from the adjusted Schmoker's and NMR methods. A cross-plot of these measurements is also provided in Figure 6.

By using the adjusted equation (Equation 11), TOC distribution for the other three wells was calculated. Figure 7 illustrates the calculated TOC for all of the four drilled wells. As the final step, by employing seismic interpreted horizons and faults and well tops data available for the studied wells, a 3D model of TOC distribution within the reservoir was built. "Upper Djeno A" and "Middle Djeno A" show the highest TOC content among the different zones and subzones. Figure 8 displays the 3D model and the locations of the wells. The mentioned subzones can be considered as the depths with the highest productivity potential in further stages of development.

Table 3

Density measurement formulas for the matrix, TOC, and kerogen.

Parameters	formulas	Values (g/cc)	Equation number
Matrix density (ρ_{mg})	$\rho_{mg} = \frac{1}{\text{INTCPT}}$	2.63	(9)
TOC density (ρ_{toc})	$\rho_{toc} = \frac{1}{(100 \times \text{SLOPE} + \text{INTCPT})}$	1.28	(10)
Kerogen density (ρ_k)	$\rho_k = \frac{\rho_{toc}}{0.8}$	1.42	(11)

Table 4

Correlation between TOC measured by NMR and indirect methods.

Method	R^2	MSE
Passey	0.26	3.57
Schmoker	0.49	11.65
Issler	0.29	13.15
Schmoker (adjusted)	0.49	0.58

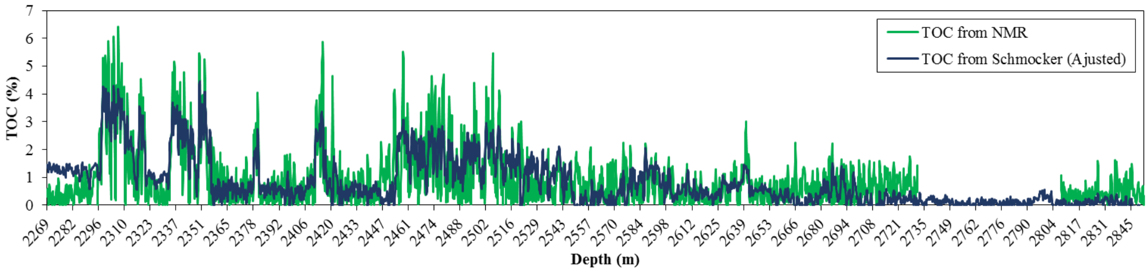


Figure 5

TOC measured by NMR and the best indirect method fit (adjusted Schmoker method).

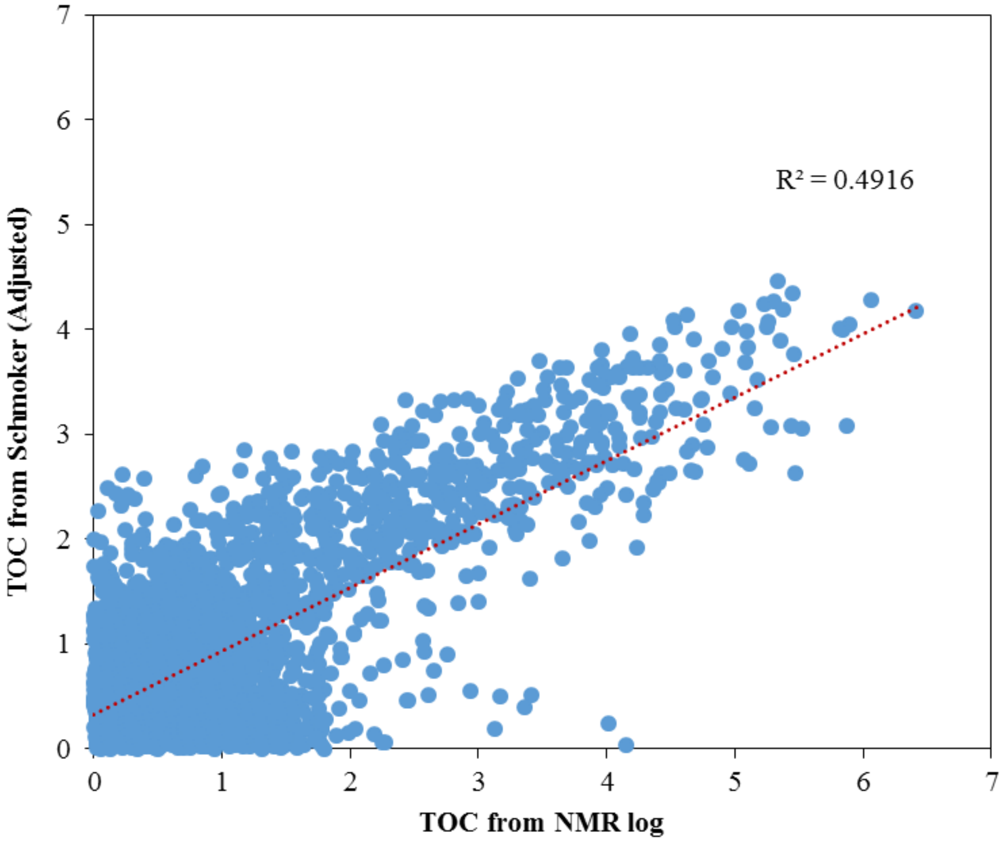


Figure 6

Cross-plot between TOC measured by NMR and adjusted Schmoker method.

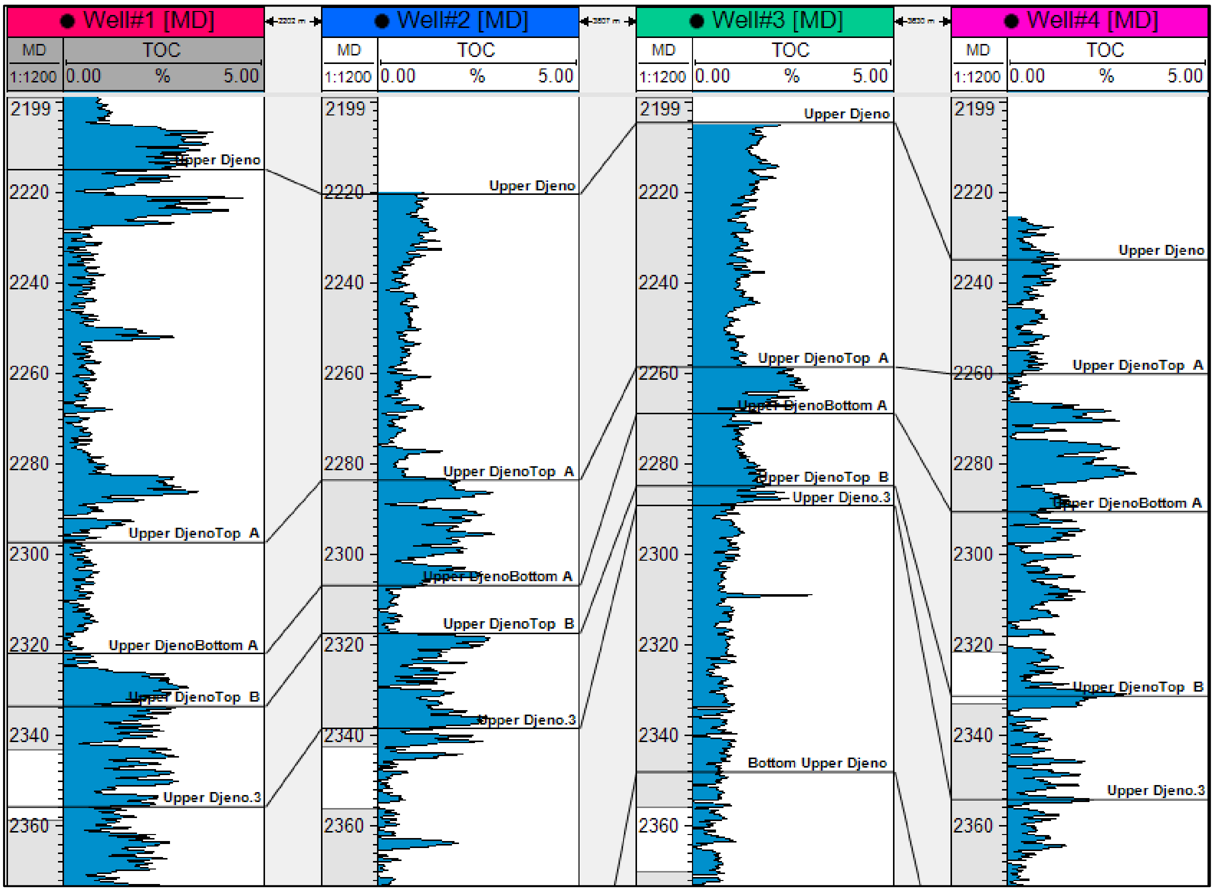
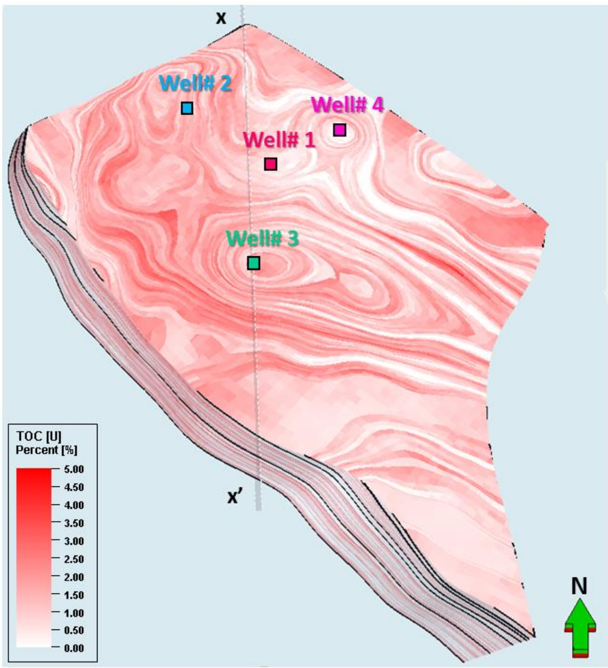


Figure 7

The calculated TOC content in the four wells drilled in the field.

a)



b)

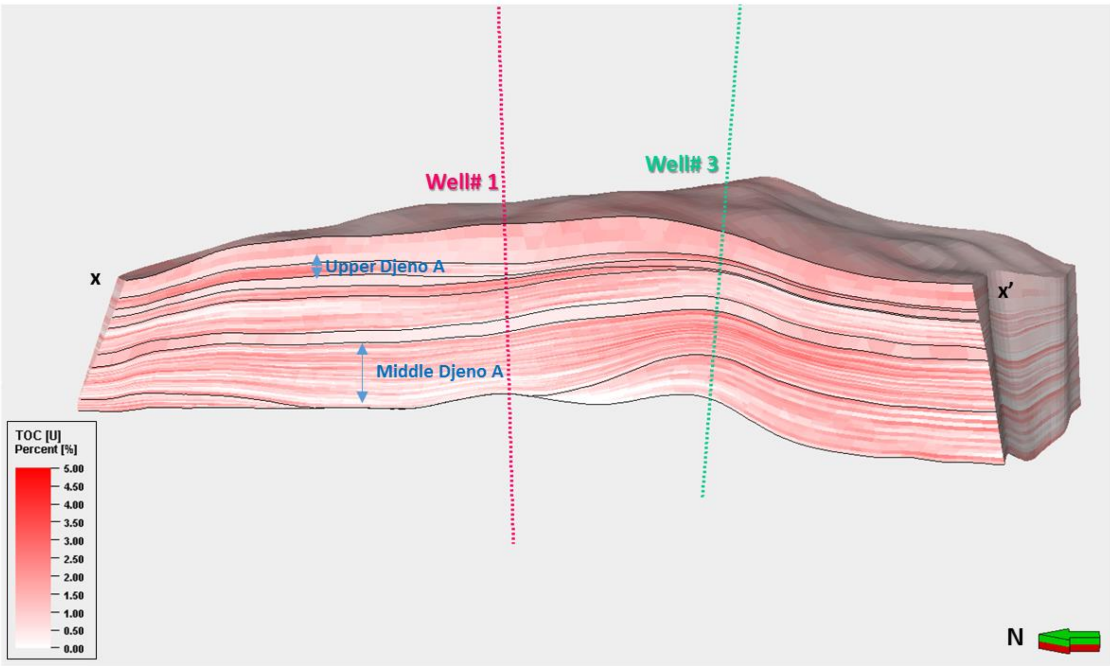


Figure 8

Constructed 3D model of TOC distribution within the reservoir: a) the horizontal section; b) the vertical section.

4. Conclusions

The total organic carbon content of a West African basin was estimated using both direct and indirect wireline techniques. As NMR log was only available for one well, we attempted to find the best correlation between the TOC calculated by indirect methods and NMR method. An adjusted Schmoker's method turns out to be the best fit regardless of its simplicity. Using the adjusted equation, the TOC was calculated for other wells within the field, and a 3D model of TOC was constructed. The following conclusions can be drawn from this study:

- Upper Djeno A and Middle Djeno A were determined to be the subzones with the highest potential of productivity, based on TOC parameter.
- Observed TOC trend from indirect wireline techniques, namely Passy's, Schmoker's, and Issler's methods, showed good agreement with NMR method, despite their limitations.
- Compared to pyrolysis method, attaining a continuous log of TOC content along the well path is the main advantage of wireline methods, in addition to their cost efficiency.
- Implementation of NMR log method can be useful for improving the TOC estimated by conventional well logs, by calibrating their results.

Nomenclature

Φ_{NMR}	Total NMR porosity
HI_f	Hydrogen index of fluid
K_{vr}	The kerogen conversion
LOM	Level of maturity
ρ_b	Bulk density

ρ_f	Pore fluid density
ρ_k	Kerogen density
ρ_{mg}	Apparent matrix density
V_k	The kerogen volume
TOC	Total organic carbon

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