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PREDICTION OF TOTAL ORGANIC CARBON CONTENTS OF ORGANIC-RICH SHALE (VARIEGATED SHALE MEMBER AND SARIR FORMATION) USING PASSY TECHNIQUE: CASE STUDY OF CRETACEOUS AGE, EASTERN SIRTE BASIN – LIBYA

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Abstract

Assessment of maturity and total organic carbon (TOC) of source rocks is mainly by core rock samples, though requires high techniques. On the other hand, well logs could provide valuable results during less time consumption. Therefore, this work is conducted to classify the maturity and estimate the total organic carbon (TOC) of the Variegated Shale member (Sarir Formation) and Sirte shale Formation (Cretaceous) by applying the Passy Technique. These formations have a thick sequence and recognized a high content of organic materials over the whole Sirte Basin (Libya). Also, the measured well logs data were taken from four wells, which are located in the Hamiemat trough (Eastern Sirte Basin), Libya. In addition, two values of a level of organic metamorphism (LOM) are used based on the documented Vitrinite Reflectance (Ro) of the study area, which is equal to 7 and 11 of the TOC evaluation. Thus, statistical average values of the estimated TOC demonstrate about 1% of the Sirte shale Formation, and they are passed 2% of the Variegated Shale member (Sarir Formation). Moreover, poor to very good potential for source rock classification within the Variegated Shale member and Sirte Shale Formations. Therefore, all the estimated TOC results by well logs fall within the documented and published studies of the source rock potential assessments of the eastern Sirte Basin, which gives validity to the applied TOC assessment technique. In summary, the gamma-ray (GR), interval travel time (ΔT), and resistivity (R) logs are the logs that have been recorded within the exploration wells of the oil fields in the hydrocarbon profile basins. Hence, the utilization of these logs to save time and cost by the Passy technique, which provides reliable results of the TOC and maturity of the source rocks in early exploration stratigraphic plan studies.

Keywords: ΔlogR method; hamiemat trough; maturity; petroleum potential; source rock; well logs.

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1. Introduction

Source rock evaluation is one of the essential geochemistry studies that is considered a main part of petroleum exploration. Also, petroleum geochemistry is conducted in thermal history study, kerogen type, and characteristics of the source rocks. In addition, most of the geochemistry studies depend on core samples, achieved by many laboratory analysis techniques. Thus, total organic carbon (TOC) indicates the quantity, but not the quality, of the organic matter. Hence, the Rock-Eval pyrolysis analyzer is one of the common techniques developed by the Institute Français du Pétrole, which has become an industry standard source rock assessment. This technique has been widely used to define the hydrocarbon potential parameters by many researchers. Abdula (2016) utilized the Rock-Eval pyrolysis analyzer within four formations that were concerned with defining and estimating the hydrocarbon potential parameters, eight samples of the Zab-1 well (south of Kalak town, Erbil Governorate). Ali (2018) studied 34 samples from five formations by applying the Rock-Eval pyrolysis, which is taken from the Bekhme-1 well (northwest of Harir town, Erbil Governorate). Whereas, Sarraj (2024) has estimated the TOC of two Cretaceous Formations (Dokan and Gulneri) in northern Iraq by applying a Rock-Eval pyrolysis analyzer and optical techniques. However, well-logging data is also widely used to determine lithofacies, depositional environment, burial history modeling, and calculating organic richness as a cheap and available technique.

Many studies related to source rock evaluation of the Sirte basin, conclude that the Cretaceous age compressed high-potential source rocks (Hallett & Clark-Lowes, 2016). Hence, previous and recent studies proved that the presence of total organic content (TOC) in commercial quantities, within different formations of the eastern Sirte Basin (Parsons, Zagaar, and Curry 1980; Gumati and Schamel 1988; Montgomery 1994; El-Alami 1996; Ghori and Mohammed 1996; Mansour and Magairhy 1996). Thus, the Sirte Shale, Etel, Rachmat, Tagrifet, Rakb, Bahi, and Nubian (Sarir) are the formations with oil-generating indications as source rocks in the eastern Sirte Basin trough. However, the Sirte Shale Formation (Campanian/Turonian) is considered a principal source rock in the whole Sirte Basin (Gumati and Schamel 1988; Montgomery 1994; El-Alami, 1996; Aboglila & Elkhalgi, 2013). Moreover, the Sirte Shale Formation has a range of values (0.5 – 4.0)% of the TOC (Parsons et al. 1980), while about 1.28%, an average value of the TOC, was reported by El-Alami (1996). Whereas both the Etal and Rachmat Formations have a range of values of the TOC from 0.1% to 7.86%. Also, the Nubian Sandstone includes enough rich shale lithofacies that are reported from eleven wells by Aboglila and Elkhalgi (2013) as a fair to very good quality classification of the TOC.

Well logs also provide a good early estimation of the total organic carbon (TOC) instead of laboratory techniques. Because the well logs are considered a cheap and quick technique that is also recorded over contentious depths in less time consumption. Thus, Hassan et al. 2023 have summarized different methods of TOC predication, while Lai et al. (2024) present a comprehensive reviewed well logging to TOC predication. Hence, many researchers are utilizing well-log data to evaluate source rocks (Omran & Alareeq, 2018). Hence, Passey et al. (1990) have published a ΔlogR technique quantifying the total organic carbon (TOC).

Therefore, porosity (Ø), resistivity (R), Gamma Ray (GR), and bulk density (ρb) are the main well logs data that have been utilized in the TOC assessment by the Passey et al. (1990) technique. However, Vitrinite reflection (Ro) and level of organic metamorphism (LOM) are two thermal maturity parameters to quality or potential predication of the source rocks as a function of the TOC (Table 1). However, core samples are not available of all exploration and development wells of the Sirte basin that allow the quality or source rocks maturity assessment. Thus, application of the Passy's technique (1990) is to define the maturity and TOC% of Variegated Shale members and Sirte Shale Formations (Cretaceous) within four wells, located in the South East Sirt Basin. Also, the TOC% results from this study will be compared with documented and published source rock evaluation of the eastern Sirte basin.

Table 1. Potential of source rock classification based on TOC, wt% (Peters & Cassa, 1994).

Quality	Poor	Fair	Good	Very good	Excellent
TOC (wt%)	0 – 0.5	0.5-1	1-2	2-4	> 2

2. Geological Background of Southeast Sirte Basin

Sirte Basin is one of the prolific hydrocarbon basins, which is located in the northern part of Libya. However, many literature reviews discussed the tectonic evolution stages of the Sirte Basin, as documented by Hallett & Clark-Lowes (2016). The tectonic configuration of the Sirte basin is mostly northwest-southeast of platforms and troughs, with two exceptions in the eastern and southern parts of the basin as shown in Figure (1). Whereas the west-east tectonic features have been documented, the trend of the eastern basin and north-south. However, the Late Cretaceous to Eocene age includes the main basin rifting and development history evolution features (Hallett & Clark-Lowes, 2016). Generally, this history could be summarized as Van Houten (1983) hypothesized that rifting resulted from drifting of the African plate over a fixed mantle hot spot leading to thinning of the cratonic lithosphere and fragmentation. This hypothesis was adopted by Harding (1984) who considers the basin to include a triple conjunction formed by three arms. Whereas Anketell (1996) has considered a shear model responsible for the tectonics of north Libyan. However, the eastern arm of the Sirte Basin includes four dominant structures in east-west orientation. These structures namely called; Hamiemat trough (Mar trough or Metem depression), Messlah- Kalanshiyu (Wasat) High, Sarir trough, and Rakb High. These structures include a complete petroleum system (El-Hawat, 2017). The Sarir (Nubian) Sandstone sequence is a giant reservoir rock (Figure 1b) within the eastern Sirte Basin (Early Cretaceous), while the Sirte Shale Formation, Rachmat Formation, and Rakb Group are rich in organic material of the Late Cretaceous. In addition, the Variegated shale member of the Sarir (Nubian Sandstone) has a thickness ranging from (100 – 660) meters, where the maximum thickness occurs at centers in the sub-basins. These shales show recognizable changes in water depth and geochemical conditions during sedimentation. It contains a floral assemblage that suggests deposition under lacustrine and marginal marine conditions during Aptian time (El-Hawat,1992). Whereas, the Sirte Shale Formation or Sirt Shale (Late Cretaceousf; Senonian/Campanian) is considered a principal source rock of the eastern Sirte Basin (Burwood et al., 2003), which is emphasized by Ambrose (2000) and

Aboglila & Elkhalgi (2013). This formation has a wide distribution within the main troughs of the Sirte Basin.

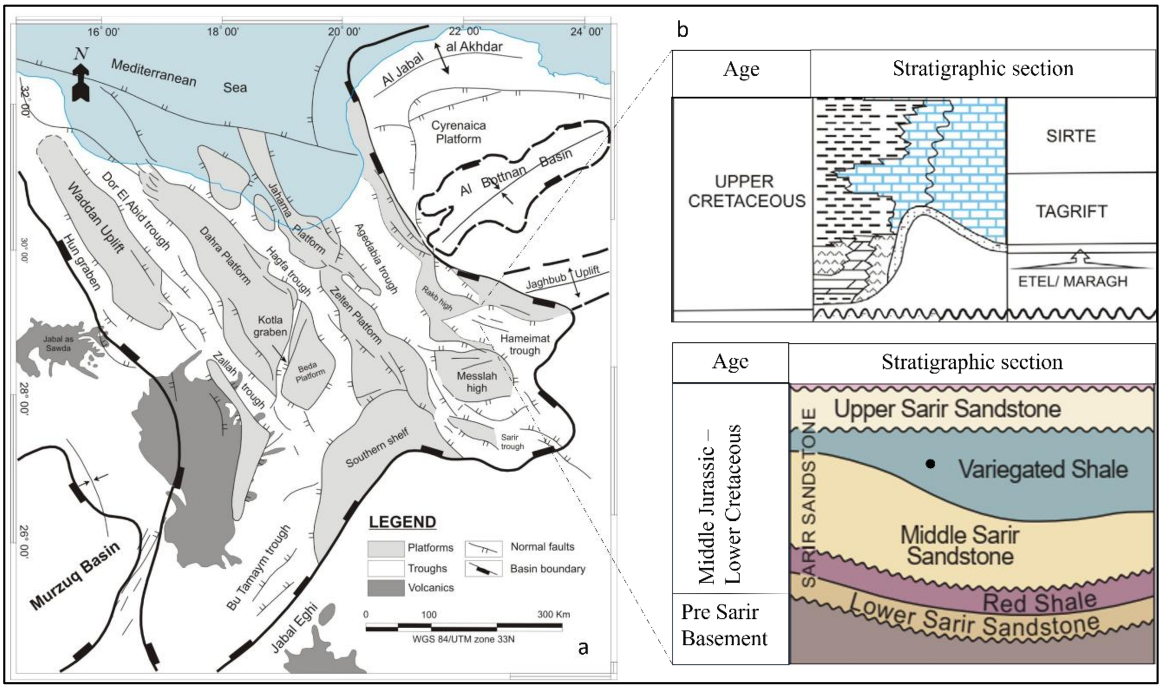

Figure 1. a) Tectonic features of the Sirte Basin map, b) General Stratigraphic section (Cretaceous), modified after (Swei, 2010; Ahlbrandt, 2001).

3. Materials and methods

Carbon element plays a primary compound that helps in the organic richness evaluation of source rocks. Because the oil or gas potential of a formation is related to the carbon content, the TOC measurement is a priority of the source rock assessment. However, each drilled well has a package of the well logging data recorded over the whole drilled or required depths. Most of the well logs are Gamma ray (GR) and interval travel time (ΔT) logs, which are important for formation correlation, rock type discrimination, and depth matching of taken core samples. Also, porosity (Ø), bulk density (ρb), and deep resistivity (Rt) logs are known as the porosity and hydrocarbon indicators (reservoir rocks assessments). In addition, the well logs have a contribution and an advantage for the source rocks evaluation. According to that, a simple linear regression equation (Equation 1) to discriminate between source and non-source rocks by Kendall (1957) is one of the techniques used for interval travel time (ΔT) and resistivity (R) logs. Also, a Passy technique (Passey et al., 1990) is the source rock potential estimates based on the logs. This technique was developed and tested by Exxon/Esso in 1979, which gives successful results for many wells worldwide. Briefly, the well logs (deep resistivity, interval travel time, gamma ray, neutron porosity, and bulk density) and level of organic metamorphism (LOM) are considered base data of the Passy application. Then, superimposed of the interval transit time (ΔT) and the deep resistivity (Rd) logs are scaled within -100 µsee/ft (-328 µsec/m) per two logarithmic resistivity cycles (i.e., a ratio of -50 µsee/ft or -164 µsec/m) to one resistivity cycle). This overlaid Rd with the ΔT and GR logs delineate baselines, which are in turn required for ΔlogR. Also, the logs overlay gives an indication of an organic-rich or not at formations depth intervals. Thus, overlay between Deep Resistivity – interval travel time logs, and Deep Resistivity - Gamma Ray log are two procedures applied to determine resistivity baseline (Rbaseline), interval baseline (ΔTbaseline), and gamma-ray baseline (GRbaseline). These baseline values are input parameters of Equations 1 and 3 to compute the TOC by Equations 2 and 4. In addition, the LOM values are a function of the Vitrinite Reflectance (Ro) value as displayed in Figure (2), which are required to compute the TOC% (Meyer & Nederlof, 1984; Passey et al., 2010). The Ro is the main criterion of thermal maturity of Kerogen (Tissot & Welte, 2013), which has a range of values in the studied formations (Sarir and Sirte Shale). Accordingly, many studies define the Vitrinite Reflectance (Ro) values of the Variegated Shale member (Sarir Formation) and Sirte Shale Formation at the eastern Sirte Basin (Albriki et al. 2021; Aldukali, Abdulhafid, and Algoul 2021; Burwood, Redfern, and Cope 2003). rocks. The Ro of the Sirte Shale Formation ranges from 0.9 to 1.38, while the Sarir Formation has a range of (0.54 – 0.57) (Aboglila & Elkhalgi, 2013). Therefore, the Passy technique is suitable for an oil-mature window of source rocks that has a range of LOM values from 6 to 10.5. Then, the LOM values will be equal to 7 and 11 as minimum and maximum values that are confirmed with the Ro values from (0.5 – 0.9) to estimate the TOC%.

$$D = -6.906 + 3.186 \log_{10} \Delta T + 0.487 \log_{10} R75 \quad (1)$$

$$\Delta LogR = Log_{10} \left(\frac{R}{R_{baseline}}\right) + 0.02 \left(\Delta t - \Delta t_{baseline}\right) \quad (2)$$

$$TOC = (\Delta LogR) \times 10^{(2.297 - 0.1688 \times LOM)} \quad (3)$$

$$\Delta LogR = Log_{10} \left(\frac{R}{R_{baseline}}\right) + 0.02 \left(GR - GR_{baseline}\right) \quad (4)$$

$$TOC = (7.3211 \times \Delta LogR) + 0.2771 \quad (5)$$

Where: D = discriminant score; R75 = resistivity at a standard temperature (24°C); ΔlogR = curves separation; R = resistivity (Ohm-m); Δt = measured interval travel time (µsee/ft); Rbaseline and ΔTbaseline = reading of deep resistivity and interval travel time corresponding to non-organic-rich rock sequence, and 0.02 = ratio of 50 µsec/ft per one resistivity cycle.

Consequently, the measured logs of the Variegated Shale member (Sarir Formation) and Sirte Formation are taken from four wells (Eastern Sirte Basin) to evaluate the TOC by the Passy technique. It is worth mentioning that, laboratory analysis is required for the core samples, which are lacking in these studied wells.

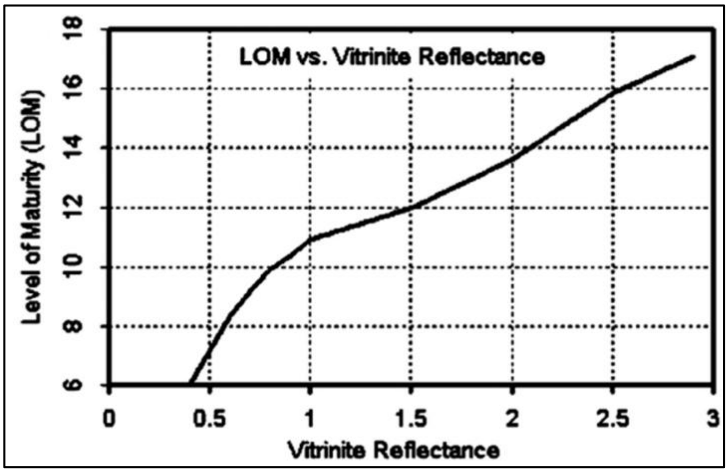

Figure 2. Level of organic metamorphism (LOM) versus vitrinite reflectance (Ro) (Meyer & Nederlof, 1984).

4. Results and discussion

Well logs can discriminate source rock potential or not within a stratigraphic sequence. Hence, the results of the calculated discriminant score (D) demonstrate fluctuation between positive and negative values. The positive values indicated the probability of source rocks, while the negative values for non-probability source rocks. Thus, the results of the score D display the Variegated Shale member and Sirte Formation within the four wells (3, 6, 7, and 8). Figure (3) demonstrates correlations of the gamma-ray (GR) and spectral gamma-ray (NGS) logs, and discriminant score (D) results of a whole Cretaceous section of well 6. In addition, figure 3 presents an overlaying gamma ray (GR), interval travel time (ΔT), and deep resistivity (Rd) logs of well 6, which provide the baselines (Rbaseline, GRbaseline and tbaseline) used to calculate the ΔlogR. Also, these overlays define a good prediction to the location of stratigraphic locate the stratigraphic sequence of source rocks. Moreover, Figures 4 and 5 show the TOC (wt%) results of each studied well, these demonstrate the overlay between the Deep Resistivity - Gamma Ray logs providing a higher TOC estimation than the overlay between the Deep Resistivity – interval travel time logs. Further, there are clear agreements of these TOC results with an exception in certain depth intervals. However, the Variegated Shale member and Sirte Formation hold the most fitting organic materials in the Sirt Basin as a result of the sedimentary environment of the basin (Hallett & Clark-Lowes, 2016). Thus, the potential of source rock classification (maturity) and an average total organic carbon (TOC) assessment of these formations are summarized in Tables 2 and 3. Generally, statistical average values of the TOC (wt%) did not exceed 1% of the Sirte Formation, and they passed 2% of the Variegated Shale Member (Sarir Formation). These average values of the TOC of the Sirte Shale Formation fall within the average quantity range (0.58 – 2.61) as documented by Peters and Cassa (1994), and from 0.18% to 5.5% as measured by Rock-Eval (Aboglila & Elkhalgi, 2013). Also, the Sirte Shale Formation (Late Cretaceous) has a 1.28% average value of the TOC (El-Alami, 1996). Further, the TOC results of the Sirte Shale formation are Compatible with an organic geochemical evaluation by Burwood, Redfern, and Cope (2003) results. On the other hand, the

Variegated Shale member is thought entered the oil generation window during the Oligocene (Hallett & Clark-Lowes, 2016). Whereas, documented TOC values of the Sarir (Nubian) Formation (Aboglila & Elkhalgi, 2013) exist within a range (0.23 – 0.69).

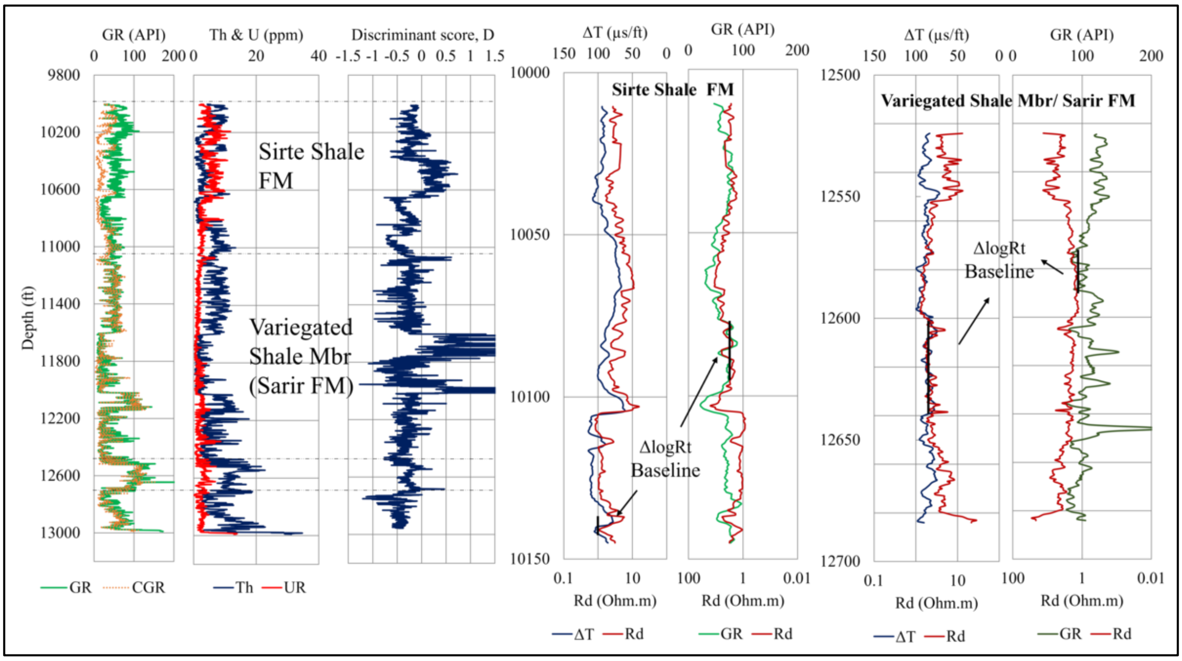

Figure 3. Gamma-ray (GR and CGR), Spectral gamma ray (Thorium and Urain), discriminant score (D), overlays between the interval travel time (ΔT), and deep resistivity (Rd) logs of the Cretaceous Formations, well 6.

Table 2. Statistical average results of the TOC (wt%).

FM/Mbr	TOC (wt%)	Wells			
		3	6	7	8
Variegated Shale	LOM = 7	4.02	1.52	2.08	3.25
	LOM = 11	0.83	0.32	0.44	0.69
	by GR	2.34	2.44	1.8	2.29
Sirte Shale	LOM = 7	2.27	4.33	3.10	2.49
	LOM = 11	0.48	0.91	0.65	0.53
	by GR	0.29	1.25	0.03	1.06

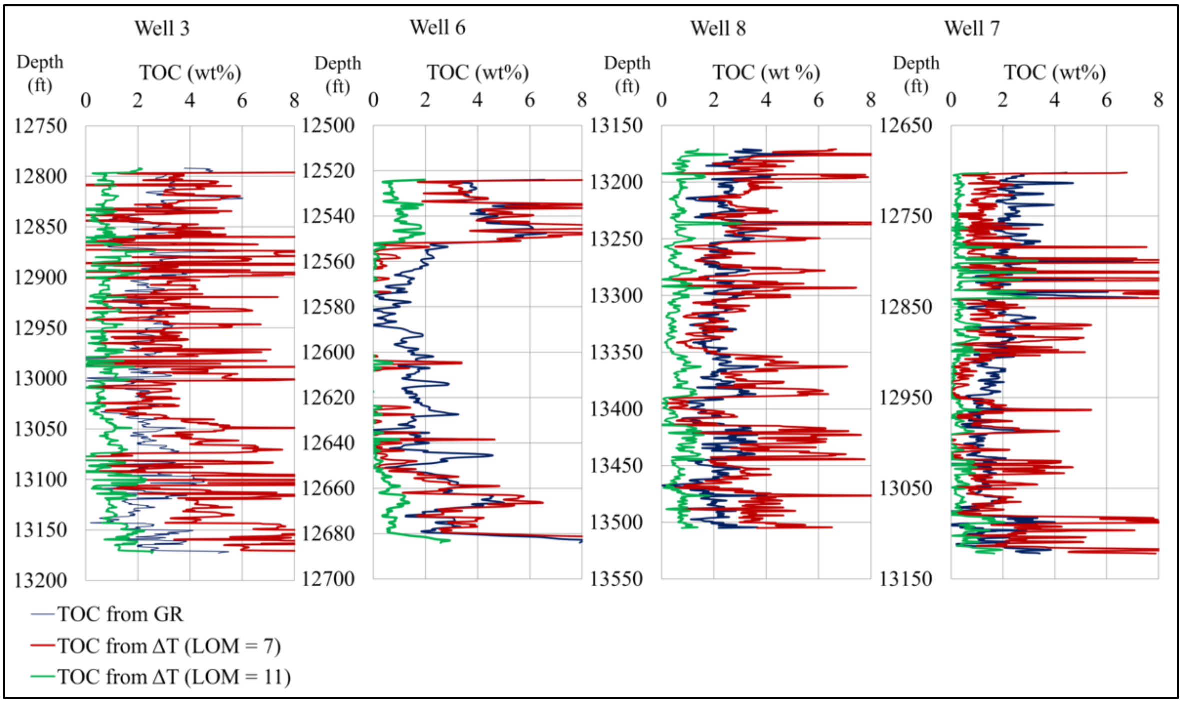

Figure 4. Total organic carbon (TOC, wt%) results of Variegated Shale member (Sarir Formation) of the studied wells.

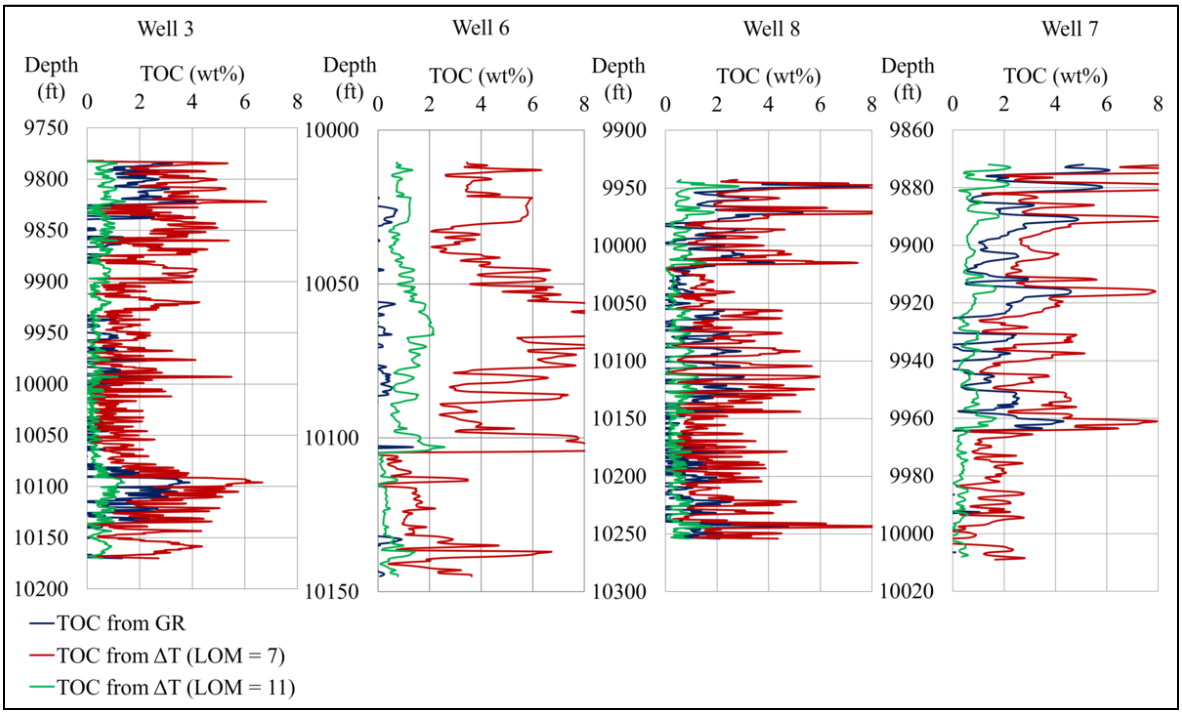

Figure 5. Total organic carbon (TOC, wt%) results of Sirte Shale Formation of the studied wells.

Table 3. Potential of source rock classification (maturity).

FM/Mbr	TOC (wt%)	Wells			
		3	6	7	8
Variegated Shale	LOM = 7	Excellent	Good	V. good	V. good
	LOM = 11	Fair	Poor	Fair	Fair
	By GR	V. good	V. good	Good	V. good
Sirte Shale	LOM = 7	V. good	Excellent	Fair	V. good
	LOM = 11	Poor	Fair	Fair	Fair
	By GR	Poor	Good	Poor	Good

7. Conclusions

A quick and easier procedure of Passy's technique could be used, especially in the early exploration of source rock instead of laboratory analysis. This technique is based on the measured well logs. Hence, the gamma-ray (GR), interval travel time (ΔT), and deep resistivity (Rd) are the main packages of logs processed to define the Total Organic Carbone (TOC) and Potential of source rock classification (maturity). These overlays in turn provide the ΔlogR of both Variegated Shale members and Sirte Formations (Cretaceous). It is worth mentioning that, the GR log is always recorded in most drilling wells of oil fields, which is known as a lithology and shale content indicator log. Whereas, the neutron porosity (Øn) and bulk density (ρb) logs are also utilizing the TOC assessment, but they are sensitive to borehole problems conditions. Then, both the GR and ΔT logs are preferred. Therefore, the evaluation of the TOC (wt %) of the studied formations discloses an agreement between the results, even the ΔlogR between the GR- Rd overlay gives higher values. In addition, statistical average values of the TOC did not exceed 1% of the Sirte Formation, and they passed 2% of the Variegated Shale Member (Sarir Formation). Also, poor to very good potential for source rock classification within the Variegated Shale member and Sirte Shale Formations. Furthermore, the TOC (wt%) results fall within the documented and published results of the source rock potential assessments of the eastern Sirte Basin, which support the TOC assessment. Consequently, the results are encouraging to apply Passy's technique of estimating TOC and the potential of source rock classification in early exploration stages of oil plays.

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