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APPLICATION OF WELL LOG DATA FOR SOURCE ROCK EVALUATION IN THE DUWI FORMATION, SOUTHERN GULF OF SUEZ, EGYPT

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تطبيق تسجيلات الآبار لتقييم صخور المصدر لتكوين الضوي، بخليج السويس، مصر

الخلاصة: نماذج عدة تم تطويرها لاستخدام تسجيلات الآبار التقليدية لحساب مجمل المحتوى العضوى وتقييم النضج الحرارى لصخور المصدر. وتم تطبيق هذه النماذج على تكوين الضوى بجنوب خليج السويس بمصر. وتعتبر تسجيلات الجاما والكثافة والصوت والمقاومة والنيترون من أهم التسجيلات المستخدمة لتعريف وتقييم صخور المصدر. وبمضاهاة النتائج بنتائج التحليلات الصخرية وجد أنه يمكن تطبيق نموذجين فقط لتقييم صخور المصدر فى منطقة الدراسة نظراً لأن معظم النماذج العملية لا يمكن تطبيقها إلا تحت ظروف معينة. ومن هذه النتائج يمكن استنتاج أن تكوين الضوى يمثل صخر مصدر عال الجودة قادر على انتاج كمية معقولة من الهيدروكربون. كما أن الكيروجين من النوع الثانى الشمعى المترسب فى بيئة بحريه تحت ظروف مختزلة.

ABSTRACT: *Several models were developed to use the conventional wireline logs for calculating the total organic carbon content (TOC) and evaluating the thermal maturity of the source rock. Application of these models for the Duwi Formation, southern Gulf of Suez, Egypt, is the purpose of this paper. Gamma ray, density, sonic, resistivity and neutron are the commonly used wireline logs to identify and quantify source rock. The obtained results compared to the Rock –Eval pyrolysis show that two models can be applied in the study area because most of the models are empirical and their validation takes place under certain conditions. The Duwi Formation represents a very good source rock capable of generating significant amounts of hydrocarbon. The kerogen is oil – prone type II, waxy sapropel related to marine plankton deposited under reducing conditions.*

INTRODUCTION

The Gulf of Suez rift basin is considered as the most prolific oil province in Egypt in spite of claiming its post maturation stage. More than 800 exploratory wells drilled in the Gulf basin resulted in 230 oil discoveries and more than 80 oil fields. A great number of researches was released and still concerned with the geological, geophysical and geochemical aspects of the Gulf of Suez. Due to the Oligocene – Early Miocene rifting, the Gulf of Suez stratigraphic succession was divided into two megasequences (Salah and Alsharhan, 1998) namely, the pre – rift megasequence extended from Cambrian to Eocene providing excellent reservoirs and source rocks (Fig. 1). Oils sourced from this succession were typically oil – prone type and occasionally oil – gas prone (Alsharhan, 2003). The source rock of the pre – rift sediments is dominantly restricted in the Duwi and Thebes formations (EGPC, 1996). The evaporites of the syn – rift megasequence provide the ultimate sealing of the generated hydrocarbons.

Numerous studies were carried out to evaluate the Gulf of Suez source rock potential in order to determine the total organic carbon content (TOC wt %) and type and thermal maturity of the kerogen based on Rock – Eval pyrolysis (e.g. RRI, 1986; Khalil, 1993; Alsharhan, 2003). Attempts to use well log data to determine the source rock potential of the Gulf of Suez were made recently by many authors such as Abdel Fattah (2007) and Elshahat et al., (2009). This paper is an attempt to evaluate the source rock potential of the Duwi Formation in the southern Gulf of Suez using well log data.

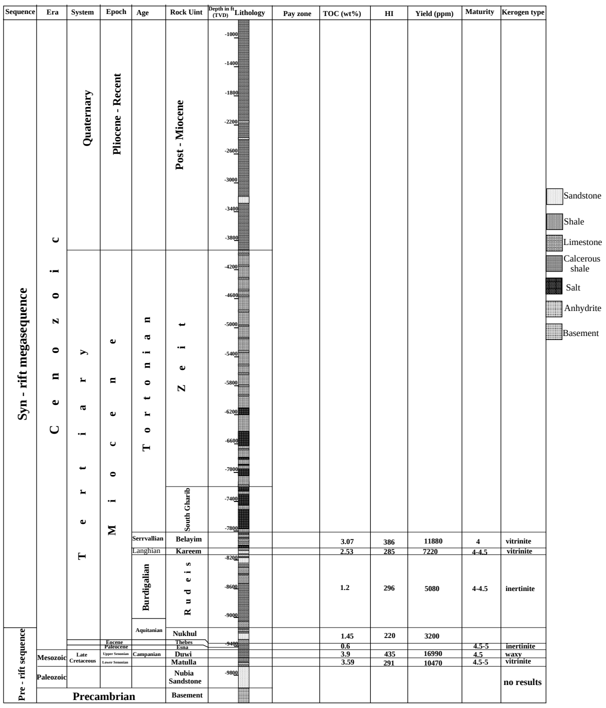

Fig. (1): Stratigraphic column of GH404-1 well, the TOC and Rock Eval results after RRI, 1986; the formations age after Bosworth et al., 1998.

The Duwi Formation (Campanian) was introduced to describe the phosphate – bearing unit, which consists of clays, sandstones and limestones of a shallow marine conditions. This formation is overlain conformably by the Paleocene Esna Formation and overlain the Lower Senonian Matulla Formation (Fig.1). According to Said (1990), a major transgression took place during Campanian furnished the optimum environment for the formation of phosphate beds.

To achieve this study, three wells were chosen. EZ391-3 and GH404-1 wells are located along the southern extension of the prolific B – trend (Fig. 2). Both wells are situated above horst structure capped by salt diapir (El Sharawy, 2006). The third well, SA – C1 is located along the Ghara trend and situated above salt pillow. The area between the two trends is a trough zone characterized by thick Miocene and post – Miocene deposits. The study area is highly dissected into numerous tilted – fault blocks varying in size where most of the faults die out at the top of the Belayim Formation (El Sharawy, 2006). In the study wells, the Duwi Formation consists mainly of intercalations of mudstone and limestone. The upper section is characterized by very high GR readings due to presence of radioactive minerals in the sediments. The thickness ranges from 163 ft in SA–C1 well to about 129 ft thick in GH404-1 well.

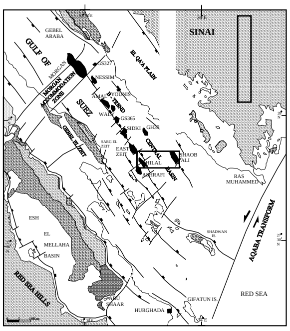

Fig. (2): Location map of the study wells showing the major structural setting in the southern Gulf of Suez (modified after Bosworth et al., 1998)

MATERIALS AND METHODS

Three wells were selected in the southern Gulf of Suez belonging to three oil fields and two different structural trends to evaluate the Duwi Formation source rock potential using the available well log data. One well, namely GH404-1 has TOC and Rock – Eval Pyrolysis results. The available well log data include gamma ray, resistivity, neutron, density and sonic. Many techniques were proposed to use the well logs response to the source rock to determine the amount of TOC. In this paper, we examined such models and determined the most applicable one in the study area according to correlation with the measured TOC. Then, the thermal maturity of the source rock was examined using different maturity indices.

Well Log Response to Source Rock:

The common utilized well logs to detect source rock by different models are:

1- Gamma ray log: presence of organic matter, which associated with uranium, resulted in increase of GR readings (Fig. 3).
2- Resistivity log: when the source rock becomes mature, free oil is present in voids and fractures, and therefore, the resistivity of source rock increases significantly by a factor of 10 or more (Mayer and Nederlof, 1984).
3- Density log: non-source shale has density matrix ranging from 2.67 to 2.72 gm/cc. Presence of organic matter will lower the rock density. In mature limestone as observed in the study wells, the rock density shows relative increasing.
4- Neutron log: measures the hydrogen index and therefore, increasing of neutron log reading will reflect the presence of source rock.
5- Sonic log: at the same conditions of compaction, and lithology, two cases were observed. Increasing sonic travel time (Δt) in immature source rock. Relative decreasing of (Δt) in mature source rock (Fig. 3).

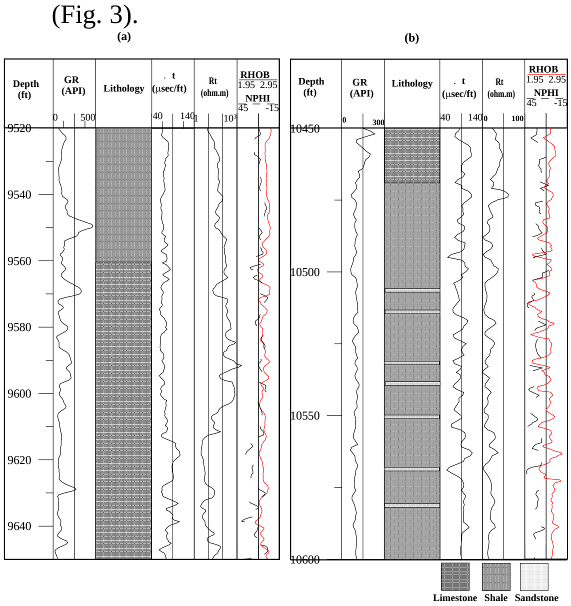

Fig. (3): Log response to source rock in the Duwi Formation:
a) GH404-1 well b) EZ391-3 well

Rock – Eval pyrolysis:

Rock – Eval pyrolysis gives information on the quantity, type and thermal maturity of the organic matter. Pyrolysis is a widely used degradation technique that allows breaking a complex substance into fragments by heating it under inert atmosphere. Rock-Eval data are expressed as mg/g of rock and include four basic parameters (Peters, 1986): 1) SI represents the quantity of free hydrocarbons present in the rock and is roughly analogous to the solvent extractable portion of the organic matter; 2) S2 represents the quantity of hydrocarbons released by the kerogen in the sample during pyrolysis; 3)S3 is related to the amount of oxygen present in the kerogen; and 4)T-max is the temperature at which the maximum rate of generation (of the S2 peak) occurs and can be used as an estimate of thermal maturity.

In addition, the ratio S2 / S3 provides a general indication of kerogen quality (type) and reveals whether oil or gas is likely to be generated (Table 1). The ratio S1/(S1+S2), or the productivity index (PI), is an indication of the relative amount of free hydrocarbons (in place or migrated) present in the sample. The productivity index (PI) increases with maturity from near zero for immature source rock to 0.15 in post – mature one. Hydrogen Index (HI) and Oxygen Index (OI) values are expressed as mg of hydrocarbons (S2 peak) or carbon dioxide (S3 peak) per gram of organic carbon (Table 1). When plotted against each other on a Van Krevelen-type diagram, information on kerogen type and maturity can be obtained. Potential yield is an indication of the produced yield of hydrocarbons from source rock at optimum maturity and is a measure of quality of source rock (Table 2).

Table (1): Type of organic matter; assumed mature OM (RRI, 1983; Peters, 1986 and Tissot et al., 1987).

Type	**HI**	**S2/S3**	**Tmax, °C**
Gas prone type III	0-150	0-2.5	400-600
Oil & gas prone type II	150-300	2.5-5	420-460
Oil prone type I	>300	>5	435-450

Table (2): Quantity of organic matter (Peters, 1986; RRI, 1984).

Quantity	**TOC**	**S1**	**S2**	**PY in ppm**
Poor	0-0.5	0-.05	0-2.5	0-2000
Fair	0.5-1	0.5-1	2.5-5	2000-6000
Good	1-2	1-2	5-10	6000-20000
Very good	>2	>2	>10	>20000

Thermal maturity of organic matter:

Several thermal maturity indices can be used to evaluate the organic matter maturity such as vitrinite reflectance (Ro), spore coloration index (SCI) and Tmax (Table 3). The first two optical indices are obtained from visual examination with reflected and transmitted light microscopy respectively. The third index, Tmax, is a product from Rock – Eval pyrolysis at which the maximum amount of S2 hydrocarbon is generated. Other indices were proposed by numerous authors. Time Temperature Index (TTI) of maturity was developed by Lopatin (1971) and introduced by Waples (1980). It depends on time and temperature as factors in thermal maturation of kerogen. This method requires two steps. The first is the construction of the geologic model for the interested interval. The second step is the temperature grid through estimating the geothermal gradient of the geologic column. A 10º C spacing is convenient. The Level of Organic Metamorphism scale (LOM) was introduced by Hood et al. (1975) based on the relationship between temperature and the effective heating time. The LOM is scaled from 0 at no burial to 20 at Anthracite/ Meta - Anthracite. According to this scale, LOM< 7.8 indicates stage of formation diagenetic methane, LOM from 7.8 to 11.6 indicates generation of oil, LOM from 11.6 to 13.5 indicates generation of condensate and wet gas; LOM >13.5 indicates formation of high – temperature Katagenetic methane. Staplin (1969) introduced the Thermal Alteration Index (TAI) scale based on the microscopic observations of both color and structure alteration of organic matter.

Table (3): Organic matter maturity indices (Peters, 1986; Hood, 1975; Waples, 1980; RRI, 1984).

Maturation	**Ro**	**LOM**	**Tmax**	**PI**	**SCI**	**TAI**	**TTI**
Immature	<0.6	<9	<420	<0.1	1-3.5	<2.5	<15
Mature	0.6-1.4	9-11.5	435-445	0.1-0.4	3.5-8.5	2.5-3	15-160
Post -mature	>1.4	>11.5	>470	>0.4	8.5-10	>3	>160
Maturation	Ro	LOM	Tmax	PI	SCI	TAI	TTI
Immature	<0.6	<9	<420	<0.1	1-3.5	<2.5	<15
Mature	0.6-1.4	9-11.5	435-445	0.1-0.4	3.5-8.5	2.5-3	15-160
Post -mature	>1.4	>11.5	>470	>0.4	8.5-10	>3	>160

RESULTS AND DISCUSSIONS

The measured TOC (wt %) of the Duwi Formation in GH404-1 well by Robertson Research International (RRI, 1986) revealed that the total organic carbon (TOC) content is ranging from 3.9 to 6.8 % in the upper section and ranging from 2.93 to 4.18 TOC (wt%) in the lower section (Table 4). The average value of the whole section is 3.9 TOC (wt%). These values indicate that the Duwi Formation is very good content of organic matter.

Applying well log models indicates that gamma ray – density crossplot (Fig. 4) reveals no linear relation. So, Schmoker (1979) and Schmoker (1981) models can't be applied. Calculation of TOC using Schmoker and Hester (1983) model based on density log (ρ) according to the following relation:

TOC (wt%) = (154.497/ ρ) – 57.261 …..……(1)

resulted in TOC (wt%) ranging from less than 1 to 6.99 with average value of 2.24 wt%, while, calculation of TOC using Myers and Jenkyns (1992) model,

Table (4): Measured total organic carbon (TOC wt%) content of the Duwi Formation in GH404-1 well (RRI, 1986).

Depth in ft	Age	Sample type	lithology	TOC (wt%)
9530-9560	Campanian	Ditch cuttings	Mudstone, brownish gray, calcareous, with 30% limestone, dark gray, lamina,	3.9
		Picked lithology	Dark gray laminated limestone	6.8
9590-9650		Ditch cuttings	Mudstone, brownish gray, calcareous, with 30% limestone, dark gray, lamina, traces of anhydrite	2.93
		Picked lithology	Dark gray laminated limestone	4.18

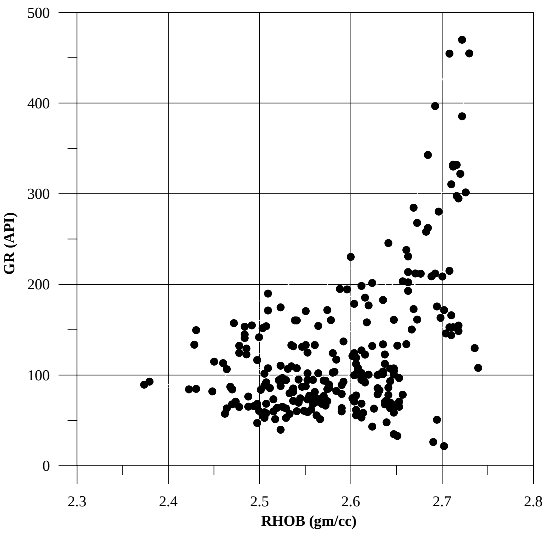

Fig. (4): Gamma ray versus bulk density of the Duwi Formation in GH404-1 well showing no linear relation exists.

$$\Phi_{fl} = \frac{\rho ns - \rho ma}{\rho fl - \rho ma} \quad ……………..……(2)$$

$$\Phi_{ker} = \frac{\rho s - \rho ns}{\rho ker - \rho ma} \quad ……….….(3)$$

$$TOC\% = \frac{0.85 * \rho ker * \Phi ker}{\rho ker(\Phi ker) + \rho ma(1 - \Phi fl - \Phi ker)} \quad .(4)$$

resulted in average TOC of 3.21% with 8.61 of maximum value (Fig. 5). This average is somehow correlated with the measured one. The proposed discriminant D that proposed by Meyer and Nederlof (1984),

$D = -6.906 + 3.186\log_{10}\Delta t + 0.487\log_{10}R75°$ ……(5)

resulted in 66% confidence in the ability to correctly classify source from non – source rock, meaning that 34% are misclassified. Applying Δlog R technique which introduced by Passey et al. (1990):,

$\Delta \log R = \log_{10} (R/R_{baseline}) + 0.02*(\Delta t- \Delta t_{baseline})$ … (6)

$TOC= \Delta \log R * 10^{(2.297-0.1688LOM)}$ ………..……….(7)

resulted in a negative separation, R_t curve to the left and Δt curve to the right (Fig. 5). This may be due to the low transit time which ranging between 57 and 107 µsec/ft with 73 µsec/ft of average value.

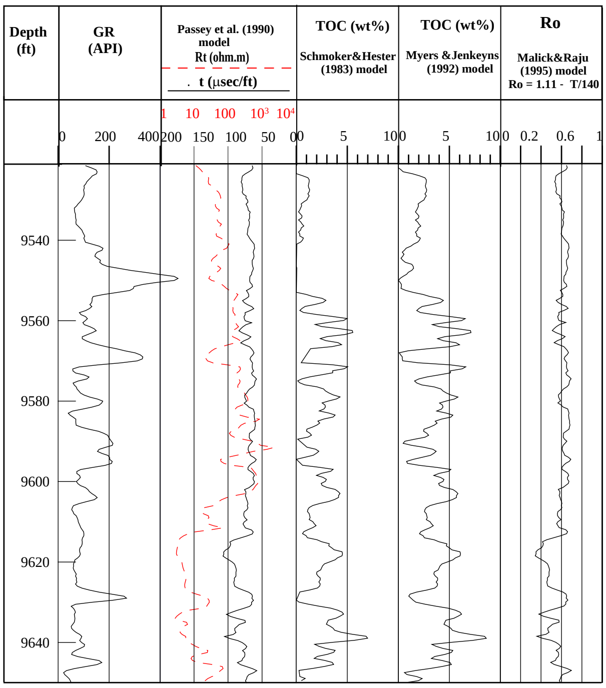

Fig. (5): TOC and Ro calculation by various models in GH404-1 well. Note the negative separation between Rt and Δt in the third track.

Using neutron and density curves instead of sonic curve resulted in the same results (Fig. 6). So, Schmoker and Hester (1981) and Myers and Jenkyns (1992) represented the only applicable models to estimate TOC% in the Duwi Formation although they give underestimated results. Therefore, we can extend application of these two models in the other wells to calculate TOC (wt%). Discriminant D reveals that the Duwi Formation in EZ391-3 well is completely non-source rock, while Equations 1 and 4 indicate that most of the section contains source rock with average values of 4.98 and 5.7 TOC wt% respectively (Fig. 7). In SA-C1 well, discriminant D indicates that the entire interval is source rock. Equation 1 gives overestimated TOC with 11.62 wt% of average value. Equation 4 gives low values with average of 2.7 TOC (wt%) as seen in Fig. 8.

Rock – Eval pyrolysis data for the Duwi Formation in GH404-1 well are presented in Table 5. From these results we can conclude that the Duwi Formation contains very good source rock capable of generating significant amounts of hydrocarbons.

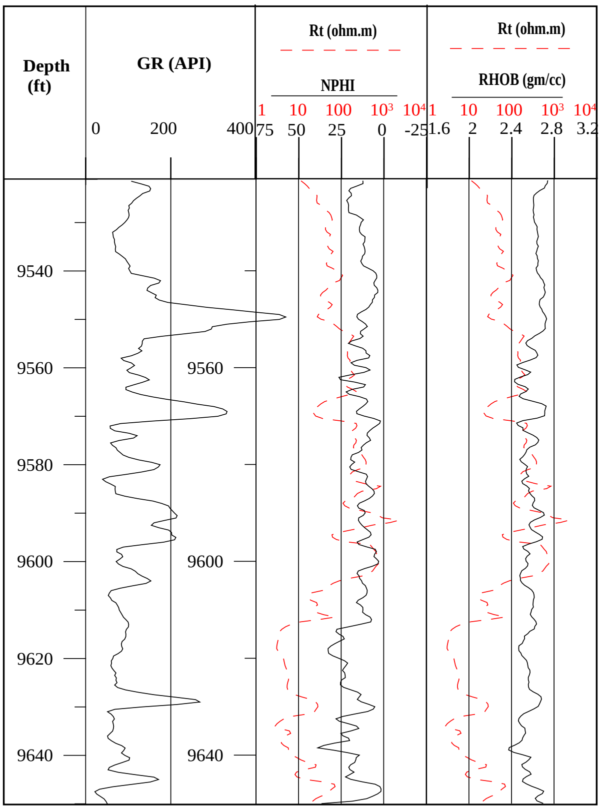

Fig. (6): Δ Log R technique using neutron – resistivity and density – resistivity overlay of the Duwi Formation in GH404-1 well.

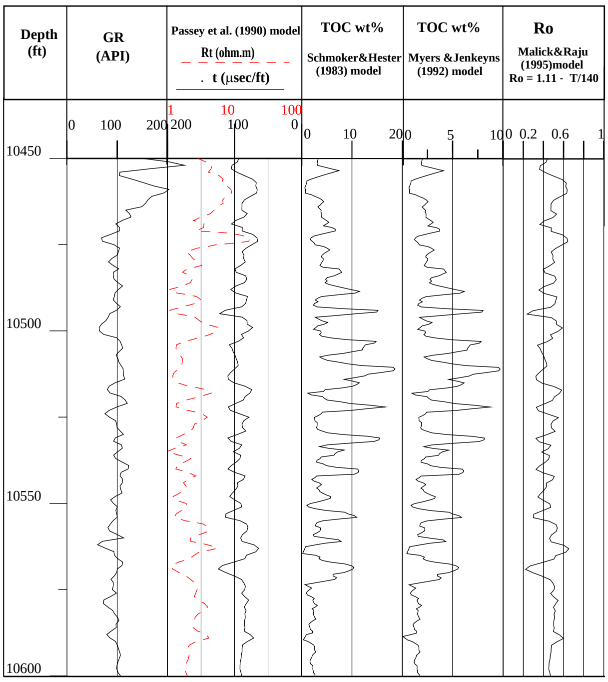

Fig. (7): TOC (wt %) and Ro calculation by various models in EZ391-3 well.

This result can be inferred from the S2, TOC and production yield values. Plotting of TOC against generation potential (S1+S2) can confirm this conclusion (Fig. 9).

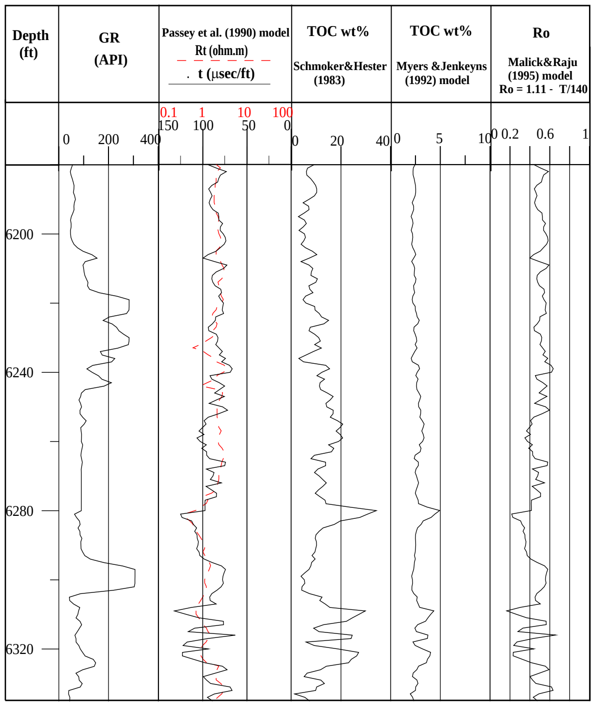

Fig. (8): TOC (wt %) and Ro calculation by various models in SA – C1 well.

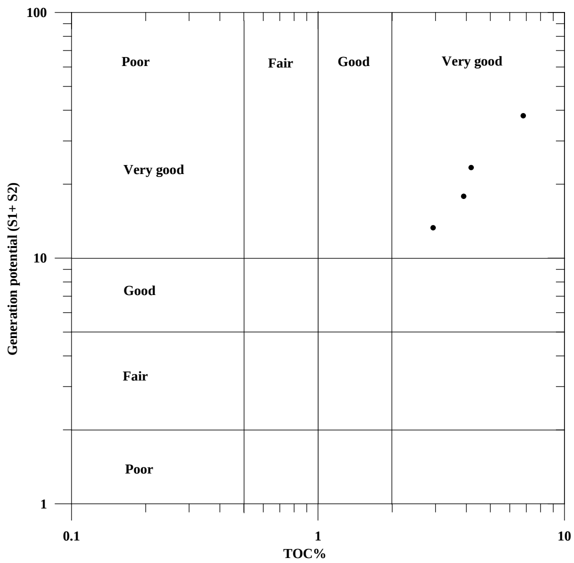

Fig. (9): Generation potential of the Duwi Formation in GH404-1 well (Hunt, 1995).

The kerogen is oil – prone type II as illustrated from the modified Van Krevelen diagram (Fig. 10). The same result can be inferred from Tmax against HI as noted in Figure 11. The low value of PI indicates indigenous oil type.

Thermal maturity of the organic matter was determined by several indices. The measured vitrinite reflectance (Ro) is 0.45% for the upper part of the Duwi Formation (Table 6) indicating immature source rock.

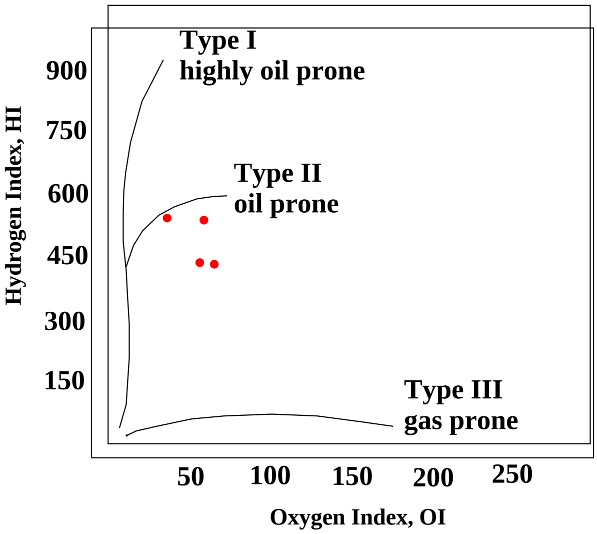

Fig. (10): Kerogen type as illustrated by modified Van Krevelen diagram (Espitalie et al., 1977).

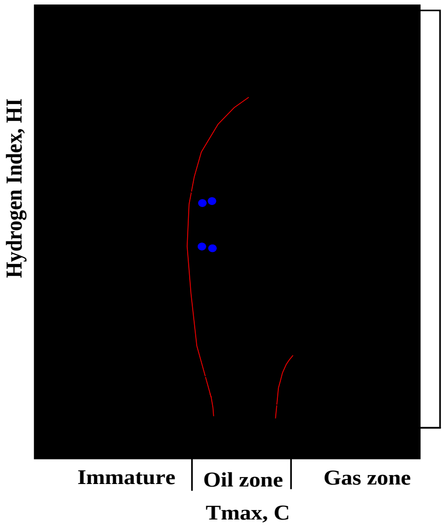

Fig. (11): Tmax versus hydrogen index indicating the type of organic matter and the level of matuity (Espitalie et al., 1977).

Table (5): Rock – Eval pyrolysis data of the Duwi Formation in GH404-1 well (RRI, 1986).

Sample depth	Sample type	Rock – Eval pyrolysis data								
		Tmax	HI	OI	S1	S2	S3	S2/S3	PI	Potential yield, ppm
9530-9560	Cuttings	435	435	57	0.89	16.96	2.22	7.63	0.05	16990
	Picked	438	543	37	1.1	36.9	2.5	14.76	0.03	36960
9590-9650	Cuttings	431	431	65	0.66	12.63	1.9	6.6	0.05	12630
	picked	434	537	59	0.93	22.44	2.46	9.1	0.04	22460

Table (6): Microscopic examination of the Duwi Formation in GH404-1 well (RRI, 1986).

Depth	Type	SCI	Ro %	Kerogen composition % by microscope			Kerogen composition by calculation from pyrolysis data %				Kerogen facies
				I	V	S	I	V	W	AS	
9530-9560	cuttings	4.7	0.45	minor	minor	100	10	35	55	-	W

I= Inertinite V= Vertinite S= Sapropel W = Waxy Sapropel AS = Algal Sapropel

However, Tmax and Spore Coloration Index (SCI) indicating mature organic matter capable of generating oil (Fig. 12). The measured SCI is 4.7 corresponding to about 10 LOM. This correlates Ro of about 0.77% in contrast with the Ro measured value (0.45 %). So, more than one index must be used to determine the level of organic matter maturity.

Therefore, SCI, Tmax, LOM and graphical plots of HI against OI and Tmax against HI indicate very good mature source rock generating significant amount of kerogen Type II. The kerogen facies is waxy sapropel indicating marine plankton debris deposited under anoxic conditions.

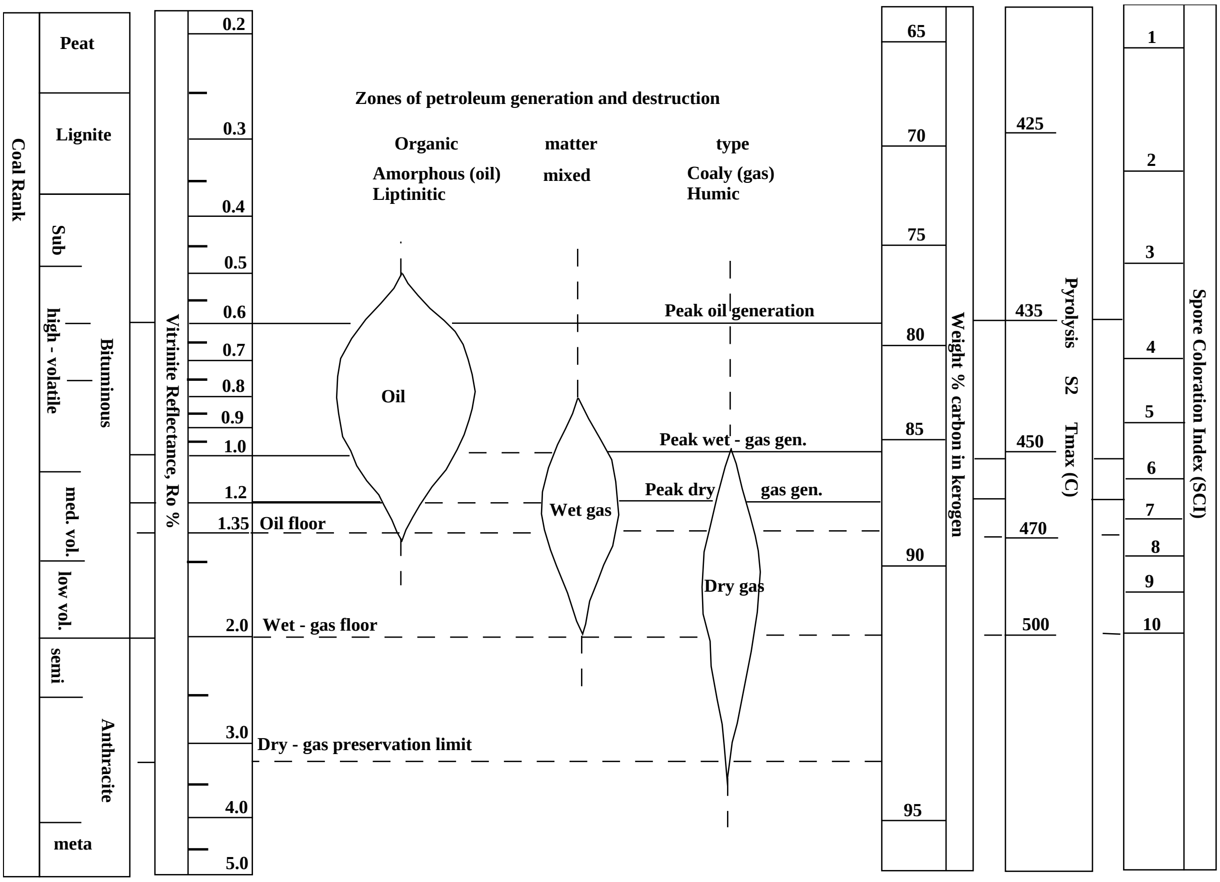

Fig. (12): Correlation of various maturation indices and zones of petroleum generation and destruction (RRI, 1986).

Construction of the burial history for the studied wells can be misleading due to the effect of the faults and hiatuses across the geologic sequence. So, missed sections and non – depositional stages will lead to underestimated TTI. However, EZ391-3 well was located in the depocenter during the syn – rift stage on the hanging walls of the fault blocks, whereas GH404-1 well was situated on the uplifted fault blocks and SA – C1 well located near the peripheral margin (El Sharawy, 2006). This physigeographic position of the three wells implied different response to the rift subsidence and sediments accumulation. As expected, EZ391-3 well was suffered a little from the effect of the lacunas and faulting. So, TTI can be estimated for EZ391-3 well in safe. The geologic burial history (Fig. 13) indicates that the onset of oil generation occurred at the Lower Miocene (TTI = 36.5). This result is correlated with that obtained from the RRI (1986) analysis. However, TTI model for the other two wells indicates immature level at that depths where TTI = 7.9; 1.18 for GH404-1 and SA-C1 wells respectively (Figs. 14 &15). If Ro = 0.77 % is correct as correlated with other thermal indices for GH404-1 well at the Duwi Formation, this means TTI = 30 at this depth. So, TTI is must be higher than 15.

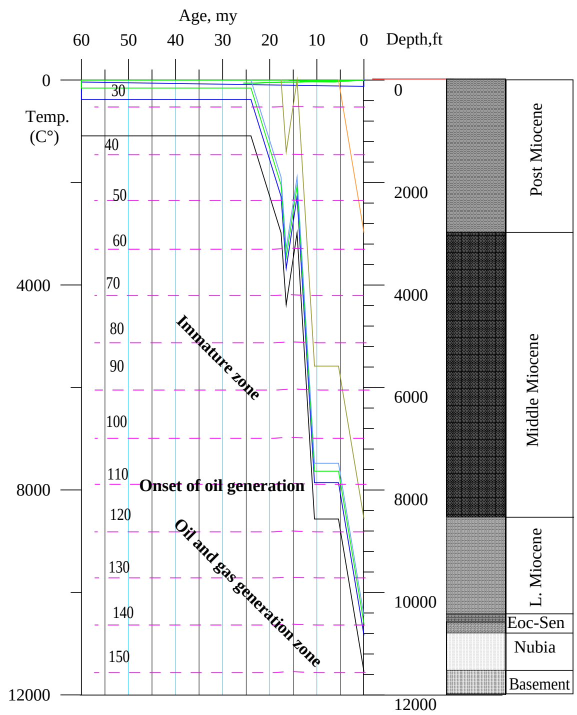

Fig. (13): EZ391-3 well burial history.

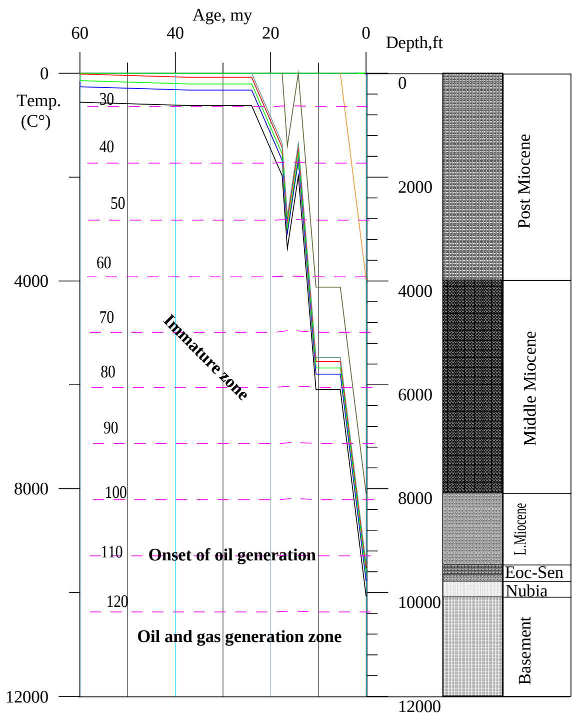

Fig. (14): GH404-1 burial history.

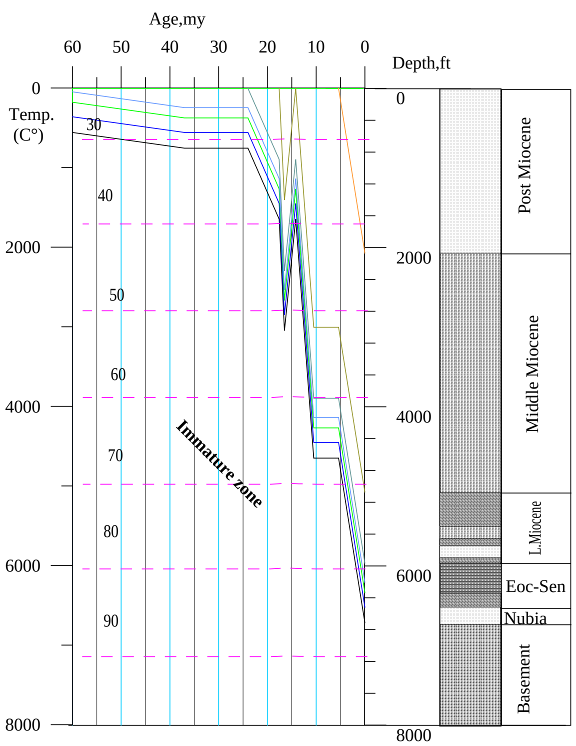

Fig. (15): SA-C1 burial history.

CONCLUSIONS

The mudstone and limestone consisting the Duwi Formation in the southern Gulf of Suez are considered as very good early mature source rock and capable of generating significant amounts of kerogen of oil – prone type II. The kerogen is waxy facies related to marine sediments deposited under reducing conditions. In case of using well logs to evaluate source rock potential, two models can be applied in the study area, namely Schmoker and Hester (1981) and Myers and Jenkyns (1992). So, the results must be calibrated with measured geochemical data because most of the models are empirical and their validation takes place under certain conditions. Contradiction may exist among various maturity indices and therefore confirmation must be used between more than one index.

Acknowledgements

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Nomenclature:

LOM = the level of maturity, 6-7 for onset of maturity for oil – prone kerogen and 12 corresponds to the onset of overmaturity for oil – prone kerogen.

$R_{baseline}$ $\Delta t_{baseline}$ = the values of the fine-grained non-source rocks chosen after superimposing the two logs.

Δt = the sonic log value, µs/ft; R75° is the log resistivity corrected to 75° F.

Φ_{fl} = water filled porosity

Φ_{ker} = kerogen filled porosity

ρ = the density, gm/cc.

ρ_{fl} = 1.05 gm/cm3, density water

ρ_{ker} = 1.1 or 1.2 g/cm3, kerogen density

ρ_{ma} = 2.7 gm/cm3, assumed mudrock matrix density

ρns = density non – source interval (average from log)

ρ_s = density source interval from log

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