JJEES

JJEES (2019) 10 (4): 194-203
ISSN 1995-6681

Jordan Journal of Earth and Environmental Sciences

Depositional Environment and Storage Capacity of Eocene Carbonate Rocks, South Western Sinai, Egypt

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Received 15 January 2019; Accepted 23 February 2019

Abstract

The main objective of the present study is to shed light on the lithostratigraphy, microfacies association, depositional environment, and the petrophysical characteristics of the Eocene carbonate rocks in southwestern Sinai, Egypt. The study area is represented by two examined sections, namely Wadi Tayiba and Wadi Feiran (from older to younger): Thebes, (Samalute equivalent Darat), Khaboba and Tanka. In this study, five microfacies were identified. These microfacies are: pellitiferous micrite, micrite, foraminiferal biomicrite, argillaceous micrite, and fossiliferous micrite. These are deposited in a platform and an open marine occurrence on the inner ramp. The obtained petrophysical results show that the Darat Formation at the Wadi Tayiba area and the Thebes Formation at the Wadi Feiran area possess the best storage capacity of the Eocene carbonate rocks in the studied area.

Keywords: Microfacies associations, Depositional environments, Petrophysical characteristics, Eocene carbonate rocks, Southwestern Sinai, Egypt.

1. Introduction

The present study deals with petrography, the paleo-depositional, environmental, and petrophysical characteristics of the Eocene carbonate rocks exposed at Southwestern Sinai along the Western side of the Gulf of Suez. The study area lies between latitudes 28º 40' 00" and 29º 10' 00" N. and longitudes 33º 00' 00" and 33º 30' 00" E. (Fig 1). The Eocene succession had been studied by several authors. Said (1990) suggested that the Eocene sediments along the Eastern side of the Gulf of Suez which are correlated with the observed sub-group, are of a limited distribution. They are represented by the deposits of Khaboba Formation. Abul-Nasr (1993 a) re-evaluated the middle upper Eocene biostratigraphy of the successions exposed at Wadi Tayiba, Wadi Matulla and Wadi Nukhul. He differentiated between the Thebes, Darat, Khaboba, and Tayiba Formations. Abul-Nasr (1993 b) recorded, for the first time, the Globigerintheka semiinvoluta zone in the Upper part of the Khaboba Formation at Wadi Warden which he assigned to the presence of the Upper Eocene in Sinai. Magdy (1997) studied the Eocene rocks in Southwest Sinai, and concluded that the conditions which prevailed during their deposition varied rapidly from South to North especially during the Middle Eocene. Ibrahim et al. (2016 a) suggested that the Eocene limestone rocks were mostly deposited under relatively warm alkaline conditions. However, the pH degrees of alkalinity during the deposition for the Darat Formation (Wadi Tayiba area) and the Thebes and Samalut Formations (Wadi Reiran area) (less in SiO_2 content) were higher than those which prevailed during the times of the Thebes, Khaboba, and Tanka Formations (Wadi Tayiba area). Ibrahim et al. (2016 b) concluded that the Eocene marine basin of deposition was relatively alkaline, close to the landmass that supplied the basin of deposition by quartz and clay.

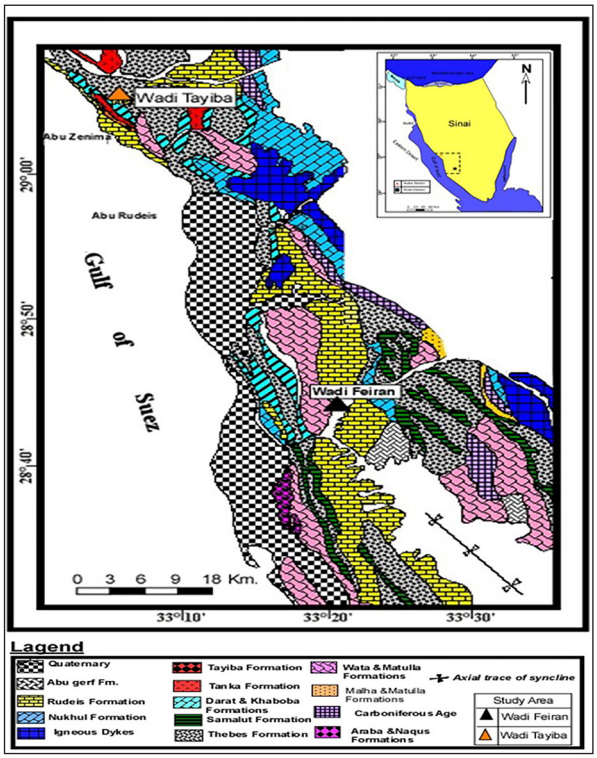

Figure 1. Location and geological maps of the study area (After Conoco, 1992).

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2. Materials and methods

The present work is focused on petrography, paleo-depositional, environmental and petrophysical characteristics of the Eocene carbonate rocks at Wadi Tayiba and Wadi Feiran areas to determine the best storage capacity. The samples were prepared and measured in the Egyptian Petroleum Research Institute (EPRI) as follows:

Sixty three thin sections were prepared (twenty six samples from Wadi Tayiba and thirty seven from Wadi Feiran) for the petrographic studies of Eocene carbonate rocks, to determine the mineralogical composition, microfacies, and paleo-depositional environment.

Forty-nine samples (sixteen samples from Wadi Tayiba) and thirty-three samples from Wadi Feiran area were examined to determine the petrophysical characteristics. The studied samples were measured using plugs of a 2.5 cm diameter and a 5cm length. All samples were cleaned and dried in an electric oven at 110 C° as maximum temperature. Bulk and grain densities, porosity, and permeability were measured using the method introduced by Dakhanova (1977). Other parameters are calculated from them. The packing index is defined by El-Sayed (1993) and the reservoir quality index (RQI) is controlled by two parameters: porosity and permeability (Dibber et al., 1996.)

2.1 Lithostratigraphy

The Eocene successions exposed in the Southwestern part of Sinai are dominated by carbonate rocks. The Eocene successions recorded in the study areas range in thickness from 152 meters (at Wadi Tayiba) to 408 meters (at Wadi Feiran), (Figs. 2 and 3) and Pl. I.

The Eocene rocks of the study areas are represented by five formations namely; Thebes (Lower to Middle Eocene), Darat and Samalut (Middle Eocene), Khaboba (Middle to Late Eocene) and Tanka (Late Eocene).

The Thebes Formation is well exposed in the study areas. It attains an average thickness of 48 meters in the Tayiba area and 268 meters in the Feiran area. Also, the Thebes Formation is characterized mainly by yellow to pale brown colored, thin–bedded, moderately-hard, and argillaceous limestones.

Age	Rock unit	Bed No.	S.No.	Thick in Meter	Lithic log.	Lithic Description
Upper Eocene	Tanka	10	25,26 23,24	8		**Massive, grayish yellow, argillaceous, fine grained and fossiliferous (*G. index index*) limestone.**
		8	22 21	14		**Varicolored, calcareous and well banded shales.**
Middle Eocene	Khaboba	7	20 19	11		**Massive, grayish yellow, argillaceous, fine grained and fossiliferous (*Tr. rohi*) limestone.**
		6	18 17	10		**Varicolored, calcareous and well banded shales.**
	Darat	5	15,16	6		**Varicolored, calcareous and well banded shales.**
		4	14 13 12 11	39		**Massive, grayish yellow, argillaceous , fine grained and fossiliferous(*M. lehneri* And *Globigerina thekasubconglobata*) limestone.**
		3	9, 10	7		**Varicolored, calcareous and well banded shales.**
Lower Eocene		2	8	8		**Massive, grayish yellow, argillaceous , fine grained and fossiliferous(*Globigerina theka subconglobata*) limestone**
	Thebes	1	7 6 5 4 3 2 1	48		**Massive, grayish yellow, argillaceous , fine grained and fossiliferous(*H. nttalli*) limestone**

lagend: limestone, Shale

Figure 2. Idealized columnar Lithic Log of the Eocene Formations measured at Wadi Tayiba area.

The Darat Formation is well-exposed in the studied areas. It is recorded in the Tayiba area with a thickness of about 60 meters, and overlies conformably the Thebes Formation. The Darat Formation is composed mainly of yellowish brown colored limestones, that are argillaceous, moderately hard, and alternated with shale.

The Samalut Formation is well-exposed in the study areas. It attains an average thickness of 140 meters in the Feiran area. Samalut Formation is equivalent to the Darat Formation in the Tayiba section.

The Khaboba Formation is recorded in the Tayiba area with a thickness of about 21 meters, and overlies conformably the Darat Formation. The Khaboba Formation is composed mainly of fossiliferous limestones.

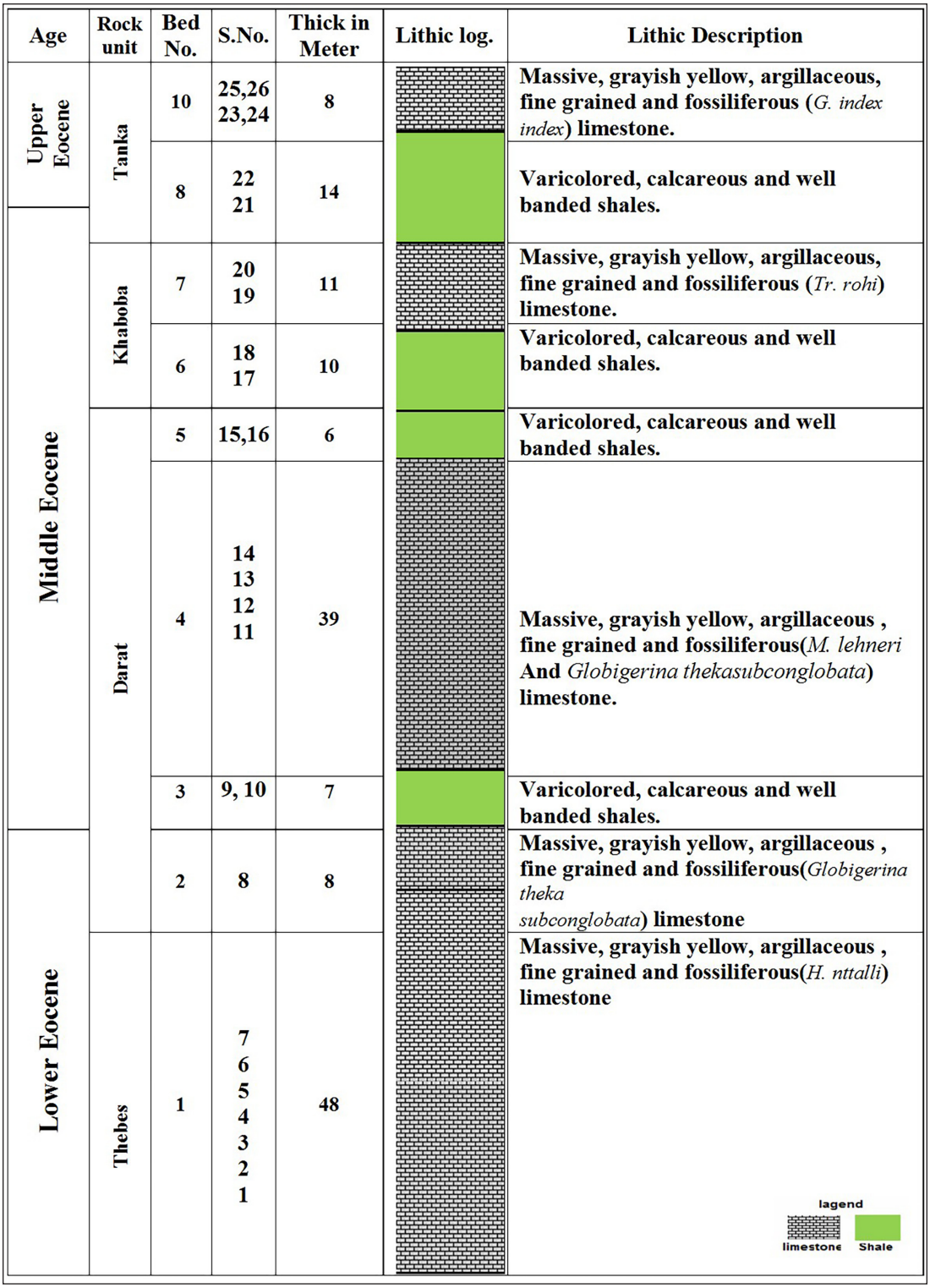


Figure 3. Idealized columnar Lithic Log of the Eocene Formations recorded at Wadi Feiran area.

The Tanka Formation in the Tayiba area attains a thickness of 22 meters. This formation conformably overlies the Khaboba Formation. The Tanka Formation is composed mainly of yellowish brown limestones that are argillaceous and moderately hard.

Plate I

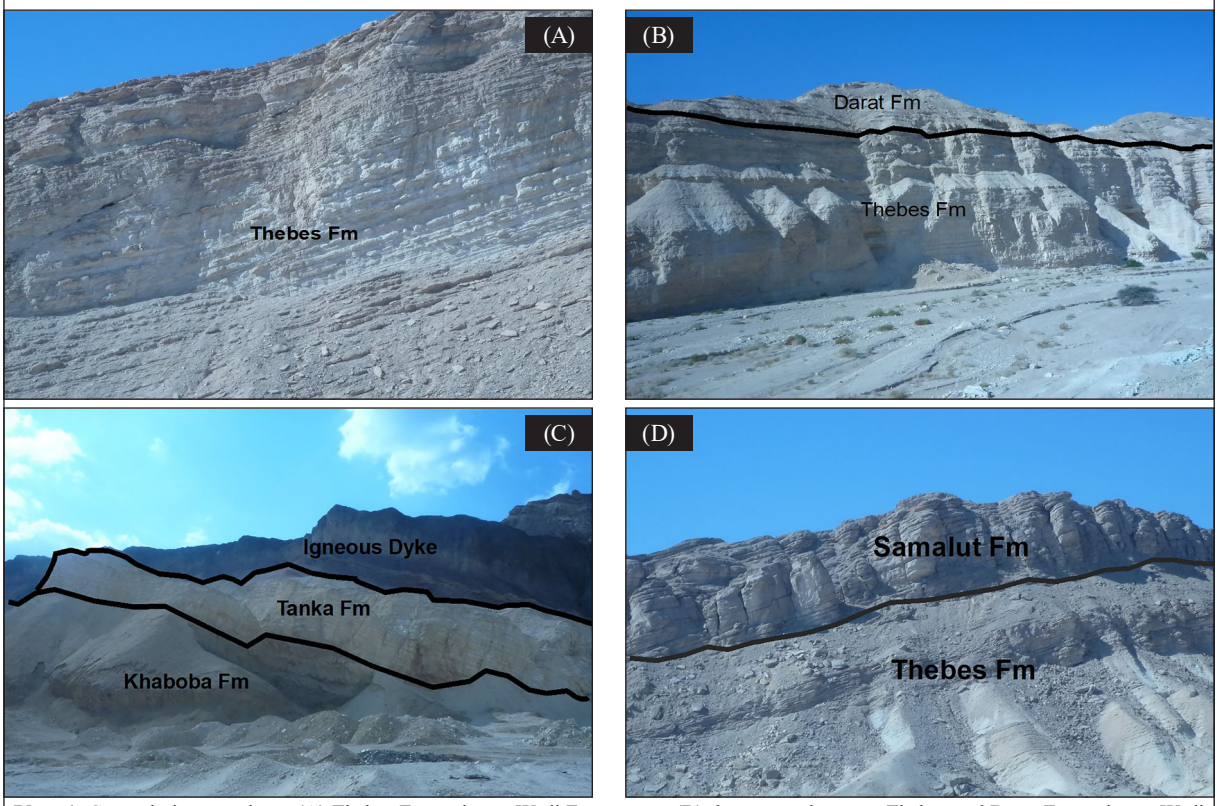


Plate 1. General views to show: (A) Thebes Formation at Wadi Ferran area, (B) the contact between Thebes and Darat Formation at Wadi Tiaba area, (C) the contact between Khaboba and Tanka Formation at Wadi Tiaba area, and (D) contact between Thebes and Samalut Formations at Wadi Ferran area.

- Microfacies Association

The study of microfacies associations was carried out to interpret the environmental conditions of deposition and to understand the digenetic processes affecting the consolidated rocks. For this purpose, the collected rock samples were thin-sectioned and examined petrographically, and the percentages of the matrix and the constituent allochems were estimated by point counting.

In the present study, the classifications of Folk (1959, 1962, and 1974), Dunham (1962) and Embry and Klovan (1972) were used. The identified microfacies associations of the studied rock sequences are shown in Fig. (4).

-Fossiliferous Micrite (Fig. 4A).

This microfacies association was detected at the Wadi Tayiba (S. No. 1, 2, 3, and 7) and Wadi Feiran (S. No. 1, 2, 4, 5, 17, 18, and 21) areas. It consists mainly of 92% carbonate for both of the Wadi Tiayba and Wadi Feiran areas. The bioclastic carbonate grains are represented by an inconsiderable amount of fossil tests and shell fragments. In this microfacies association, terrigenous materials are preset in the form of clay which is the main constituent (5%) for both of the wadi Tayiba and Feiran areas. Spary calcite cement was present in a considerable amount; it seems to be formed during restricted recrystallization process. Dolomite is represented by a few rhombs scattered in micrite matrix 1% for both Wadi Taybia and Feiran. Texturally, according to Dunham (1962) and Embry and Klovan (1972), these microfacies associations are considered as mudstones. The presence of fossiliferous micrite microfacies association indicates a deposition under shallow marine calm water conditions. Under this condition, micrite can be formed either by the action of bacteria-producing ammonia which reacts with the carbonates to form ammonium carbonates which in turn react with calcium sulphate of the seawater precipitate calcium carbonate. Consequently, this microfacies association indicates a deposition in the shallower setting of the inner neritic.

-Arigillaceous Micrite (Fig. 4B).

This microfacies association was detected at the Wadi Tayiba area (S. No. 4, and 6). It consists mainly of 75% carbonate. The presence of spary calcite cement in an inconsiderable amount favors the little pore space available for its formation in the micrite matrix. In this microfacies association, terrigenous materials are present in two forms; clay and silty grains up to 25%. Texturally, according to Dunham (1962) and Embry and Klovan (1972), this microfacies association is considered as mudstone, (Tables 1 and 2). The study of this microfacies association points to the lack of strong currents leading to a rapid rate of precipitation of micro-crystalline ooze (23). The terrigenous materials in the form of clay and silts, present in a considerable amount, can be attributed to the increase of terrigenous contents delivered into the site of deposition either by running water, fluctuation of sea level, or as a result of strong currents and turbulence in deeper waters.

-Foraminiferal Biomicrite (Figs. 4 C and D).

This is recorded in the Lower and Middle Eocene at Wadi Feiran area and was detected at Wadi Tayiba only in Middle Eocene. It consists of 90% carbonate, with a considerable proportion of allochems (more than 10%).

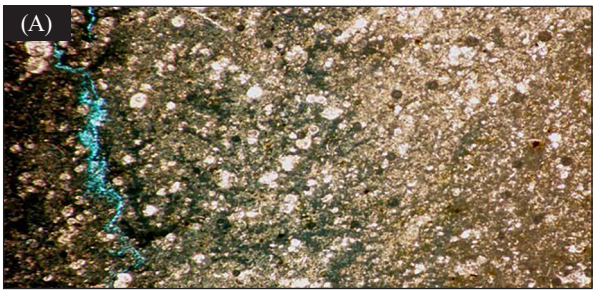
The bioclastic carbonate grains (allochems) are represented by foraminiferal tests of a small size and good sorting. Texturally, according to Dunham (1962) and Embry and Klovan (1972), this microfacies association is considered to be as a packstone. The study of this microfacies association suggests that currents were not sorting or persistent enough to winnow away the microcrystalline ooze which remained as a micrite matrix Folk, (1974). The presence of well-sorted foraminiferal tests, which have relatively small sizes and the nature of micrite, indicates the deposition in the marine environment at the middle part of the outer neritic zone Fig. 4 (C and D).

-Micrite (Fig. 4E).

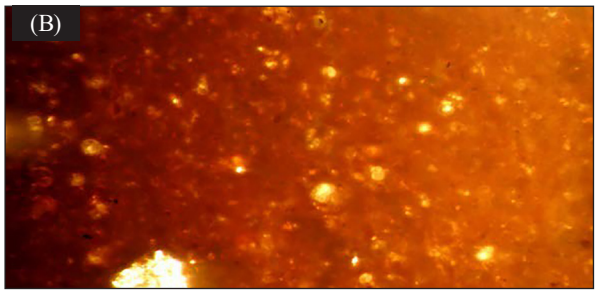
This microfacies association was observed at the Wadi Feiran area. According to the classifications of limestone based on depositional texture, Dunham (1962) and Embry and Klovan (1972) believe this microfacies is to be considered as mudstone. The study of the microfacies association reveals a rapid rate of precipitation of the microcrystalline ooze with a lack of strong currents (Folk, 1959). Micrite was formed either by direct inorganic precipitation of aragonite, or by producing aragonite needles within the tissues of calcareous algae as shown in Fig. 4E. Consequently, this microfacies association was thought to be deposited under relatively shallow marine conditions in the deeper part of the inner neritic zone in quiet water.

-Pellitiferous Micrite (Fig. 4F).

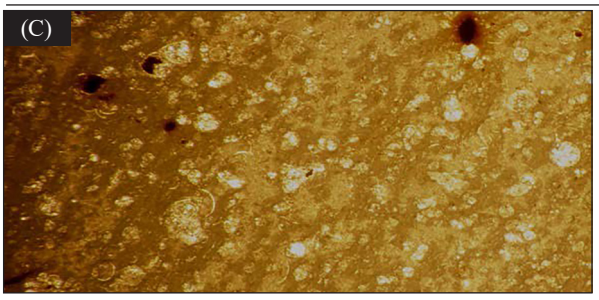
This microfacies association was detected at the Wadi Tayiba area. The non- bioclastic carbonate grains are represented by homogeneous pellets, composed of aggregates of lime mud, well-rounded and embedded in a micrite matrix. The terrigenous material in this microfacies is present up to 5% only in the form of clay. It is clear that the packing of these rocks impose a certain maximum on the amount of pellets (less than 10%). Most pellets are formed in situ, whereas the hydraulic condition in deep waters may form from lime mud pellets. Texturally, according to Dunham (1962) and Embry and Klovan (1972), this microfacies association is considered as mudstone, as shown in Fig. 4 (F).



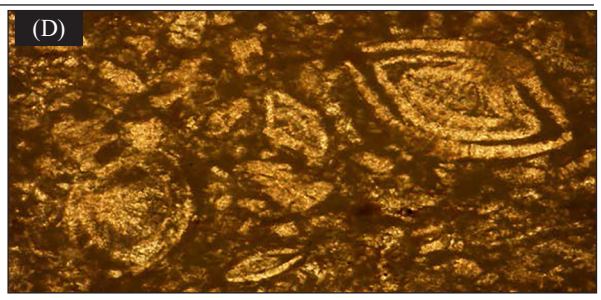
(A): Photomicrograph showing fossiliferous micrite microfacies association consists mainly of microcrystalline ooze with unconsiderable proportion of allochems. Thebes Formation, Wadi Tiaba area. Ordinary Light X 10.



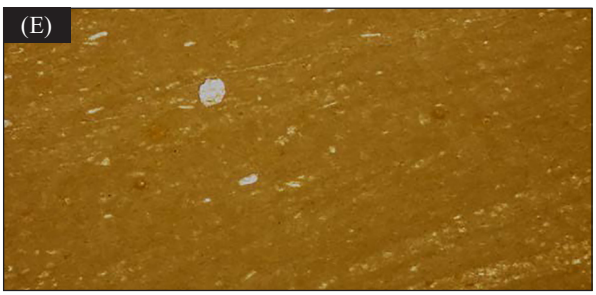
(B): Photomicrograph showing argillaceous micrite microfacies association consists mainly of microcrystalline ooze. Thebes Formation, Wadi Tiaba area. Ordinary Light X 10.



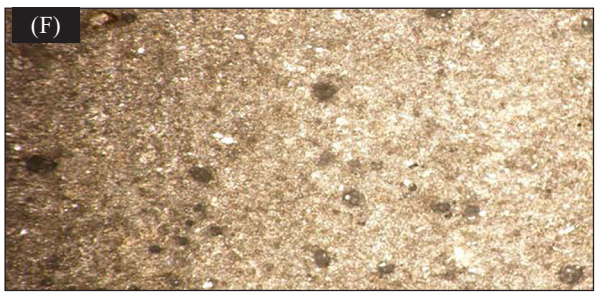
(C): Photomicrograph showing Foraminiferal biomicrite microfacies association, consists mainly of microcrystalline ooze with considerable proportion of allochems. Thebes Formation, Wadi Ferran area. Ordinary Light X 10.



(D): Photomicrograph showing Foraminiferal biomicrite microfacies association consists mainly of microcrystalline ooze with considerable proportion of allochems. Samalut Formation, Wadi Ferran area. Ordinary Light X 10.



(E): Photomicrograph showing Micrite microfacies association consists mainly of microcrystalline ooze with unconsiderable proportion of allochems. Thebes Formation, Wadi Ferran area. Ordinary Light X 10.



(F): Photomicrograph showing Pellitiferous micrite microfacies association consists mainly of microcrystalline ooze with un-considerable proportion of allochems. Darat Formation, Wadi Tiaba area. Ordinary Light X 10.

Figure 4. The Identified microfacies associations of studied Eocene rocks .

-Depositional Environment.

The petrographic studies on the Wadi Tayiba and Wadi Feiran areas reveal that several depositional environments which can be summarized according to Flugel (2004 and 2010). The depositional patterns of the Eocene microfacies associations recorded in the Wadi Tayiba and Wadi Feiran areas are characterized by shallow waters, generally a few to tens of meters deep. Salinity varies from essentially a normal marine to somewhat higher. Circulation is very moderate, and water conditions are favourable for organisms to live as shown in Tables (1 and 2).

Table 1. Microfacies association depositional patterns (Wadi Tiayba) area.

Age	Formation	Described microfacies type	Microfacies association according to Embry and Klovan (1972)	Standard microfaccies SMF	Facies Zone (FZ) V	Occurrence on flat-top platform	Occurrence on ramp
Upper Eocene	Tanka	Agril. Micrite; S. No. 24	Mudstone	23	8	Restricted plateform	Inner ramp
	Khaboba	Micrite; S. No. 23		23	8		
Middle Eocene		Agril. Micrite; S. No. 19, 20		23	8		
	Darat	Foraminiferal biomicrite; S. No. 12	Packstone	9	7	Open marine	
		Foraminiferal micrite; S. No. 11, 13. 14	Mudstone	19	8	Restricted platform	
Lower Eocene		Pellitiferous micrite; S. No. 8		19	8		
	Thebes	Agril. Micrite; S. No. 4, 5, 6		19	8		
		Fossiliferous micrite; S. No. 1, 2, 3, 7		19	8		

Texturally, the Eocene sediments in the Wadi Tayiba and Wadi Feiran areas vary but contain considerable amounts of lime mud. The prevailing rock types are variable limestones interbedded with a calcareous shale (marlstone). The grain types show a little variety of textures from a packstone to mudstone with little pelleting of micrite matrix. The terrigenous clastic is characterized by the presence of quartz silt, siltstone and calcareous shale intercalated with limestone in the lower segregated beds. Biota is represented by foraminifera. Consequently, according to Flugel (2004 and 2010), the depositional patterns of the Eocene microfacies associations in the Wadi Tayiba and Wadi Feiran areas show a sequence of both uniform and cyclically alternating, open and restricted marine and evaporate environments of the carbonate facies zone (7 and 8), on the inner ramp.

Table 2. Microfaciesassociation depositional patterns of (Wadi Feiran).

Age	Formation	Described microfacies type	Microfacies association occurring to Embry and Klovan (1972)	Standard microfacies SMF	Facies zone (FZ)	Occurrence on flat-top platform	Occurrence on ramp
Middle Eocene	Samalute	Foraminiferal biomicrite; 31, 32, 33, 34, 35, 36, 37	Packstone	9	7	Open marine	Inner ramp
		Micrite; 24, 25, 26, 27, 28, 30	Mudstone	23	8	Restricted platform	
Lower Eocene	Thebes	Micrite; 13, 14, 19, 20	Wackstone	19	8		
		Foraminiferal biomicrite; 7, 8, 9, 10, 11, 15, 16	Packstone	9	7	Open marine	
		Fossiliferous micrite; 1, 2, 4, 5, 6, 17, 18, 21	Mudstone	19	8	Restricted platform	

-Petrophysical Characterization

The reservoir characterization of any hydrocarbon-bearing system depends on its petrophysical parameters (porosity, permeability, grain and bulk densities, packing index, porosity ratio, and quality reservoir index). To achieve this, the collected samples were studied to determine the storage capacity as shown in Tables (3 and 4).

In the present study, forty-nine samples were selected, (Sixteen samples) from the Wadi Tayiba area and (thirty-three samples) from the Wadi Feiran area to detect the petrophysical characteristic of these areas.

The petrophysical results reveal that the Wadi Tayiba, Darat Formation (T11, T12, T13, and T14) samples, have higher porosity and permeability values associated with a decrease in the grain density and the bulk density. The quality-reservoir index, packing index and porosity ratio increase as the porosity and permeability increase (Abd El-Hafez et al., 2015).

Table 3. Petrophysical parameters of the investigated samples (Wadi Tayiba area).

Age	Form.	S. No.	Grain density	Bulk density	Porosity	Per.	Packing index	Porosity ratio	QRI
Upper Eocene	Tanka	T24	2.57	2.331	9	0.023	1.1025	0.09890	0.0008
		T23	2.66	2.3583	11	0.005	1.1279	0.12359	0.001
	Khaboba	T20	2.55	2.1071	17	0.035	1.2101	0.20481	0.0006
Middle Eocene		T19	2.66	2.3673	11	0.02	1.1236	0.12359	0.0005
	Darat	T14	2.53	2.0205	20	.027	1.2521	0.25	0.0004
		T13	2.57	2.1145	18	0.052	1.2154	0.21951	0.009
		T12	2.44	1.4434	41	0.304	1.6904	0.69491	0.002
		T11	2.58	1.3476	48	0.556	1.9145	0.92307	0.003
Lower Eocene		T8	2.69	2.5089	7	0.009	1.0721	0.07526	0.004
	Thebes	T7	2.68	2.2144	18	0.958	1.2102	0.21951	0.016
		T6	2.68	2.1518	20	1.203	1.2454	0.25	0.018
		T5	2.69	2.0245	25	0.26	1.3287	0.33333	0.003
		T4	2.56	1.6308	36	0.65	1.5697	0.5625	0.005
		T3	2.5	1.7472	30	0.625	1.4308	0.42857	0.006
		T2	2.61	1.4936	43	0.6	1.7474	0.75438	0.004
		T1	2.68	2.2211	17	0.575	1.2066	0.20481	0.010

The petrophysical results reveal that Wadi Feiran, Thebes Formation samples (F15, F16, F17 and F18) have higher porosity and permeability values associated with a decrease in the grain density and the bulk density.

Table 4. Petrophysical parameters of the investigated samples (Wadi Feiran area).

Age	Form.	S. No.	Grain density	Bulk density	Porosity	Per.	Packing index	Porosity ratio	QRI
Middle Eocene	Samalut	F37	2.58	2.2822	12	0.006	1.1304	0.1304	0.065
		F36	2.61	2.3492	10	0.005	1.1110	0.11111	0.11111
		F35	2.62	2.5884	1	0.04	1.0122	0.01010	0.007
		F34	2.65	2.6226	1	0.06	1.0104	0.01010	0.005
		F33	2.59	2.5692	3	0.04	1.0080	0.030920	0.003
		F32	2.66	2.5853	0.5	0.01	1.0288	0.03092	0.066
		F31	2.67	2.572	3	0.02	1.0381	0.03092	0.065
		F30	2.39	2.5943	3	0.01	0.9212	0.0392	0.009
		F29	2.64	2.1405	11	0.007	1.233	0.12359	0.007
		F28	2.42	2.278	14	0.004	1.0623	0.16279	0.005
		F27	2.4	2.0912	13	0.003	1.1476	0.14942	0.003
		F26	2.47	1.916	22	0.432	1.2891	0.28205	0.038
		F25	2.48	1.7564	29	0.861	1.4119	0.40845	0.066
		F24	2.68	2.1814	19	1.29	1.2285	0.23456	0.065
	Thebes	F21	2.73	1.91	30	1.72	1.4293	0.42857	0.102
		F20	2.69	2.2683	16	1.78	1.1859	0.19047	0.070
		F19	2.66	1.7307	35	6.17	1.5369	0.53846	0.137
		F18	2.68	1.8146	32	10.54	1.4769	0.47058	0.180
		F17	2.67	1.8225	32	5.41	1.4650	0.47058	0.146
		F16	2.69	2.0213	25	1.22	1.3308	0.33333	0.058
Early Eocene		F15	2.7	1.7579	35	9.62	1.5359	0.53846	0.212
		F14	2.69	2.1335	21	6.38	1.2608	0.26582	0.138
		F13	2.68	1.7852	33	3.12	1.5012	0.49253	0.127
		F11	2.62	2.1185	19	1.62	1.2367	0.2367	0.081
		F10	2.7	2.0621	24	0.13	1.3093	0.31578	0.022
		F9	2.7	2.0256	25	0.27	1.3329	0.33333	0.033
		F8	2.7	2.0135	24	0.14	1.3212	0.31578	0.023
		F7	2.71	2.0044	26	0.43	1.3520	0.351350	0.044
		F6	2.68	2.1211	21	0.5	1.2634	0.26582	0.043
		F5	2.7	1.981	26	0.66	1.3629	0.35135	0.052
		F4	2.65	2.0071	24	0.35	1.3203	0.31578	0.075
		F2	2.7	1.7442	35	0.55	1.5479	0.53846	0.041
		F1	2.68	1.8619	32	0.4	1.4393	0.47058	0.035

From the obtained petrophysical results, it can be concluded that the Wadi Tayiba area (samples T11, T12, T13, and T14 of Darat Formation) and the Wadi Feiran area (samples F15, F16, F17, and F18 of Thebes Formation) represent the best storage capacity (Figures 5 and 6).

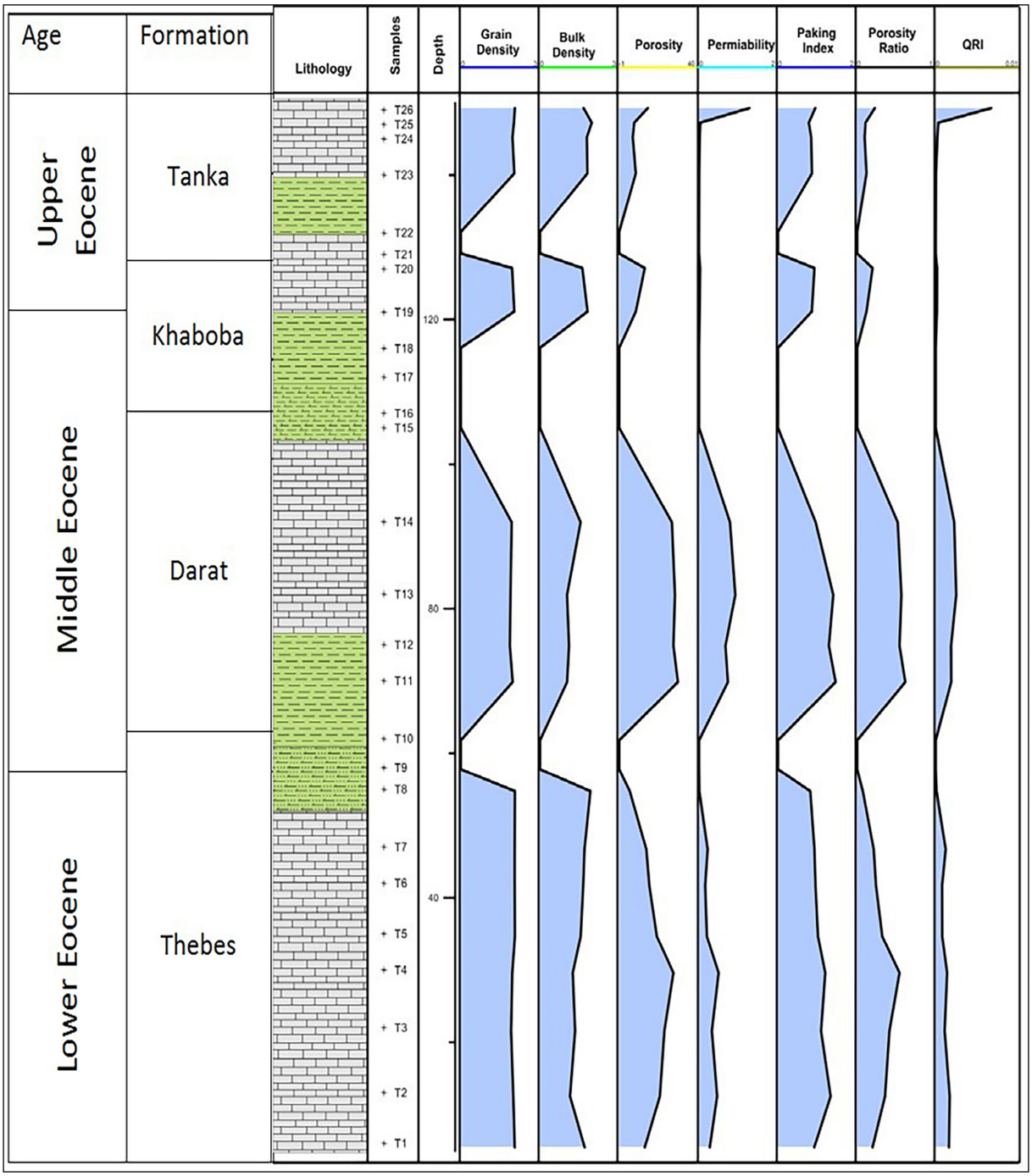


Figure 5. Vertical distribution of the petrophysical properties in Wadi Tiayba area, South western Sinai, Egypt.

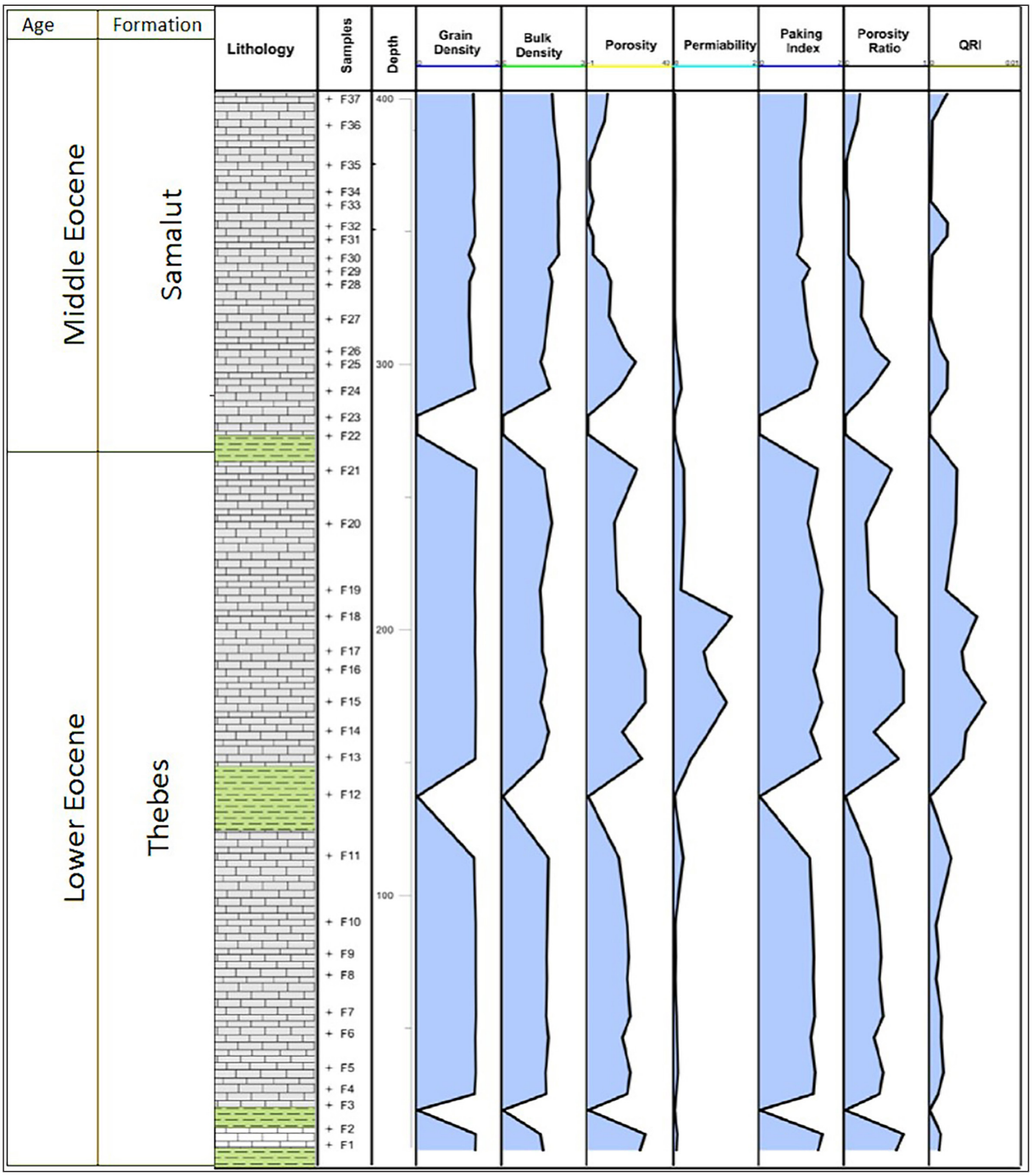


Figure 6. Vertical distribution of the petrophysical properties in Wadi Ferran area, South western Sinai, Egypt.

3. Conclusions

The Eocene successions exposed in the Southwestern part of Sinai are dominated by carbonate rocks. The Eocene successions recorded in the study areas range in thickness from 152 meters (at Wadi Tayiba) to 408 meters (at Wadi Feiran).

The petrographic study of the carbonate rocks reveals the following observations:

Lower Eocene: Fossiliferous micrite and argillaceous fossiliferous micrite were detected at the Wadi Tayiba area. At Wadi Feiran area, the detected microfacies associations are fossiliferous micrite Foraminiferal biomicrite and micrite.

Middle Eocene in the study areas is represented by the Darat and Khaboba formations (Wadi Tayiba area) and Samalut Formation (Wadi Feiran area). At Wadi Tayiba area Pellitiferous micrite, fossiliferous micrite and foraminiferal biomicrite were detected, while at the Wadi Feiran area, micrite and foraminiferal biomicrite were the main microfacies.

Upper Eocene: The Tanka Formation in (Wadi Tayiba area) is represented by Micrite and argillaceous micrite.

The obtained petrophysical results reveal that the Darat Formation at Wadi Tayiba area and The Thebes Formation at Wadi Feiran area showed the best storage capacity.

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