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ORIGINAL PAPER

Source rocks evaluation, hydrocarbon generation and palynofacies study of late cretaceous succession at 16/G-1 offshore well in Qamar Basin, eastern Yemen

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Abstract Subsurface Late Cretaceous succession has been recovered from 16/G-1, an offshore exploratory well that located in the Qamar Basin, eastern Republic of Yemen. This paper deals with the study of source rocks, maturation, hydrocarbon evaluation, and palynofacies of the Late Cretaceous Mukalla and Dabut Formations of the Mahra Group. These two formations consist of an intercalation of argillaceous, carbonates, siltstones, sandstones and coal layers. The sedimentary organic matter as amorphous organic matter, phytoclasts and palynomorphs are investigated and identified under transmitted light microscope. Spores, pollen, dinoflagellates, algae, fungi, and acritarchs in addition to foraminiferal lining test have been also identified. The optical and organic geochemical studies were used to evaluate the source rock, maturation and its hydrocarbons potentiality. The thermal alteration index, vitrinite reflectance, rock-eval pyrolysis, and palynofacies were also used. The upward increase in the relative abundance of marine versus terrestrial input reflects a major marine transgression and retregration cycles from Campanian to Maastrichtian stages. The Mukalla and Dabut Formations are late immature to mature stages with kerogen types II and III. The hydrocarbons generation potentiality of two formations is oil and wet gas prone indicators.

Keywords Source rocks · Maturation · Hydrocarbon generation · Palynofacies · Mukalla · Dabut · Qamar Basin · Yemen

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Introduction

The Qamar Basin is believed to contain sedimentary sequences of Jurassic and younger ages, but the deeper wells did not penetrate depths more than the Upper Cretaceous succession (Mukalla Formation). Until now, no available publications have addressed the organic maturity and source rock potentiality of this basin.

Rock-eval pyrolysis/total organic carbons (TOC), T_{max}, vitrinite reflectance (R_0), and thermal alteration index (TAI) were applied to evaluate the source rock availability and its potential to generate hydrocarbons in the Qamar Basin (Fig. 1). This work is also performed together with palynofacies analyses. The integration of the two types of the analysis including the optical and organic geochemical methods is thought to be capable of providing a reliable source rock assessment in a relatively poorly studied basin.

Geological setting and previous work

The first detailed unpublished stratigraphic work in Yemen was carried out by Wetzel and Morton in the period 1948–1950 (Beydoun 1964, 1966), who surveyed the area from Al-Mukalla City on the southeastern Yemeni Coastal to the Damqawt Village near the Omani border of Mahra Province (Fig. 1). The stratigraphic sedimentary sequence of Yemen is predominantly Mesozoic and Cenozoic in age; however, Paleozoic metasediments are also known to exist but only in few areas in eastern Yemen. The Mesozoic sequence starts with basal shallow marine sandstone sediments (Kuhlan Formation) which were deposited during the regional transgression of Early to Middle Jurassic. It was followed by open marine carbonates of the Shuqra Formation, and the Madbi and Nayfa Formations of the Late Jurassic to the earliest Cretaceous. In the Early Cretaceous, rifting spread

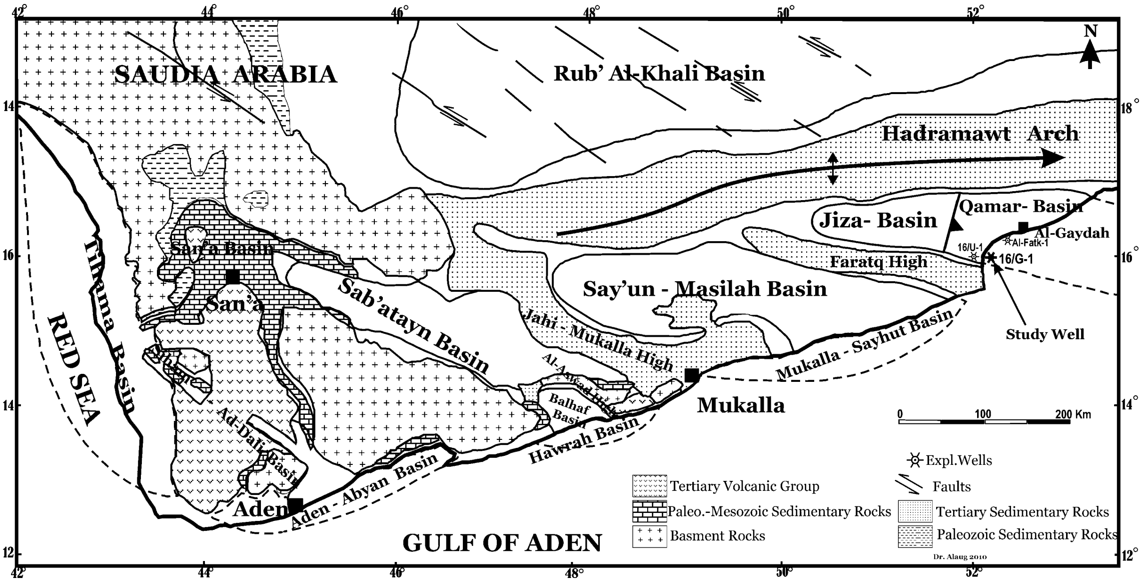

Fig. 1 Location map of sedimentary basins in Yemen, Qamar Basin and 16/G-1 offshore studied well

eastward through which the Jeza, Qamar basins were formed. Thick Early–Middle Cretaceous syn-rift carbonates and clastics of the Sa'ar and Qishn Formations of the Mahra Group were deposited. In the latest Middle Cretaceous, late syn-rift carbonates were accumulated in eastern Yemen (Fartaq Formation of Mahra Group) while paralic clastics were deposited in the west (Qishn Formation and Harshiyat Formation of the Tawilah Group). The clastics/carbonates transition is oscillated from west to east in eastern Yemen in response to sea level changes and locally modified by the remnant rift topography (Bott et al. 1992; Bosence 1997).

Similarly, west to an eastward clastics/carbonates transition typified the Late Cretaceous although the carbonates were able to prograde further eastward into Qamar Basin. Early Tertiary marine transgression flooded the whole eastern Yemen, extending to Jahi-Mukalla High and Al-Aswad High (Fig. 1), forming a widespread shallow marine carbonate deposition of Umm Er Radhuma Formation of the Hadramawt Group. The regression events during the Late Paleocene to Early Eocene reduced the area of the carbonate shelf giving way to lagoonal and sabkha environments. In Middle Eocene, a transgression was started to cover a wide area of shallow marine carbonate environments followed by a regional hiatus (regional uplift) in the Late Eocene to Late Oligocene, which preceded rifting, and seafloor spreading in the Gulf of Aden (Brannan et al. 1997; Beydoun et al. 1998). The mainland of Yemen remained emergent from this time onwards, while underwent gradual subsidence in the Gulf of Aden and Qamar Bay allowed the accumulation of thick syn-rift clastics and carbonates of Oligo-Miocene age (Taqah and Sarar Formations). The post rift phase of Qamar Basin is represented by an accumulation of marine clastics (Shihr Group).

The Qamar Basin is a polyphase rift basin, lies in Mahra Province of eastern Yemen (Fig. 1). It was probably originated as part of an extensive rift system, which developed during the Late Jurassic to Early Cretaceous as a result of the break-up of southern Gondwanaland and separation of India and Madagascar (Bosence 1997). The last events in Qamar Basin were formed during the Oligocene to Holocene time that associated with reactivation of the rifting of the Indian Ocean and subsidence of Gulf of Aden (Birse et al. 1997; Bosellini et al. 2001). The offshore Qamar Basin has been thermally subsided and reheated as result of spreading in the Gulf of Aden started in the Middle Miocene (Brannan et al. 1997).

Generally, Qamar Basin extends east–west from about longitude 51° W in the west of Mahra Province to the offshore of Qamar Bay–Gulf of Aden of Indian Ocean in the east (Fig. 1). To the north, the Hadramawt Arch separates the Jeza and Qamar basins from the southern flank of Rub Al-Khali Basin, which extends toward the northward across Yemen and the Saudi Arabia borders. To the south, the Masilah–Fartaq high separates Qamar Basin from other Mesozoic and Cenozoic depocentres in the Gulf of Aden and the Masilah areas (Brannan et al. 1997; Sharland et al. 2001).

The subsurface sedimentary rocks of Late Cretaceous age comprising of the Mukalla, Dabut, and Sharwayn Formations forming the upper part of Mahra Group. These formations conformably overlie the lower part of Mahra Group which was not penetrated by the exploratory drilled wells in Qamar Basin and unconformably underlie the Cenozoic deposits of Hadramawt Group (Brannan et al. 1997; Beydoun et al. 1998). Mahra Group in the eastern Yemen is subdivided into several formations (Beydoun

1964; Beydoun and Greenwood 1968; Beydoun et al. 1998). Tawilah Group is the lateral equivalent in south-western areas of Yemen and adjacent basins as Jeza and Masilah–Sayun basins, which possess more clastics than Mahra Group.

Aims and objectives

Because of the poor exploration of the Qamar Basin, this study is focusing on hydrocarbon source rock evaluation and maturation stage of Upper Cretaceous Mukalla and Dabut Formations of 16/G-1 offshore exploratory well in the Qamar Basin, eastern Yemen. This could be achieved by assessing the petroleum generation potential of selected organic-rich core and cutting samples occurring within the Qamar Basin. Sedimentary organic matter can also be used as indicators for petroleum and source rock correlation, because the walls of spores and pollen are resistant and can be used as indicators to the thermal alteration in the process of petroleum genesis. Moreover, palynomorphs can indicate the geological age and sedimentary environments of studied succession. Since palynology is a useful scientific method in petroleum source research. Vitrinite reflectance supplements these data and visual assessment of palynomorph colors to determine the maturation levels of the organic matter contained in the Upper Cretaceous subsurface samples of 16/G-1 well, Qamar Basin, eastern Yemen (Fig. 1).

Material and methods

In this work, 131 subsurface core and cutting samples were selected to study the Upper Cretaceous Mukalla and Dabut Formations encountered in the 16/G-1 offshore well, Qamar Basin (Fig. 1). The samples were prepared for the palynofacies analysis and microscopically studies for all the particulate organic matter occurring in it. Neither oxidation nor ultrasonic probe was carried out during the processing due the importance of particles may be destroyed by such procedures. The studied succession is mainly composed of an intercalation of shale, calcareous shale, carbonate, siltstone, sandstone, mudstones, and coal layers. The process of samples selection to extract the palynological materials was carried out at the laboratories of the Geological Department of Assiut University, Egypt and Taiz University, Yemen. A routine palynological preparation scheme, involves washing of sample, treatment with hydrochloric acid (35%) and hydrofluoric acid (40%). The organic matter residual of acids treatment is used to mounting on one slide before sieving it by using 10-mm nylon sieves and make another slides. Thereafter, the residue of organic matter was directly mounted on glass microscope slides by using glycerin jells. The residual of organic materials mounted by glycerin jell without any oxidation treatment, carrying out TAI, optical investigation, and quantitative analysis of organic matter under the transmitted light microscope. Quantitative analyses of the palynomorph associations were based on counts of 200 specimens for most samples, but where the samples were poorly fossiliferous, fewer numbers were recorded. The geochemical analysis raw data for subsurface core and cutting samples was carried out and provided by Yemeni Petroleum Exploration and Production Authority.

Source rock evaluations

Source rocks are generally organic-rich fine-grained sediments that are naturally capable of generating and releasing hydrocarbons in amounts to form commercial accumulations (Hunt 1996). In the present study, the organic geochemical raw data of 45 core, side-well core and cutting samples from the depth interval of 2,437–3,885 m studied well are considered (Table 1). This depth interval is penetrating the Dabut and Mukalla Formations (Mahra Group). To evaluate the quality on sedimentary organic matter in a potential source rocks, both geochemical and microscope methods are commonly used.

Rock-eval pyrolysis and TOC

Rock-eval pyrolysis is used to determine the petroleum potentiality, thermal maturity of the organic matter and its ability to generate oil and/or gas. The utmost method is widely used for determining the amount and type of the organic matter in the rock and measuring petroleum potential via this method (Espitalie et al. 1977, 1984). The pyrolysis gives rise two parameters; S_1 and S_2, both are expressed as kilograms of hydrocarbons per ton of rock. S_1 measures the amount of free hydrocarbons that can be volatilizing out of the rock without cracking the kerogen (mg HC/g rock) while, S_2 measures the hydrocarbons yield from cracking of kerogen (mg HC/g rock).

The organic geochemical log is considered as the most powerful tool for understanding and interpretation of source rocks evaluation and hydrocarbons generation of studied section. It records data such as TOC, S_1, S_2, production index (PI), petroleum potentiality (PP), T_{max} (maximum of temperature), and hydrogen index (HI) versus depth of 16/G-1 exploratory offshore well (Fig. 2). Figure 2 shows the idealized geochemical log based on TOC/rock-eval pyrolysis data of Mukalla and Dabut Formations of Upper Cretaceous subsurface succession. The interpretation of this geochemical log indicates good quality and quantity of source rock succession, especially within Mukalla Formation (Fig. 2).

Table 1 Rock-eval pyrolysis/TOC data of 16/G-1 offshore well

Depth (m)	TOC	S_0	S_1	S_2	PI	HI	T_{max} (C°)	PP
2437.5	0.51	0.01	0.17	1.06	0.14	207.8	436	1.24
2460.7	0.6	0.02	0.36	0.87	0.29	145	431	1.25
2462.5	0.51	0.01	0.34	0.93	0.27	182.4	431	1.28
2464.5	0.71	0.02	1.16	1.51	0.43	212.7	430	2.69
2465	0.66	0.02	0.43	1	0.3	151.5	429	1.45
2470	0.7	0.01	0.14	0.52	0.21	74.3	428	0.67
2652	0.52	0.01	0.15	0.18	0.44	34.6	416	0.34
2672	0.95	0.01	0.15	0.78	0.16	82.1	435	0.94
2701	0.95	0.01	0.16	0.4	0.28	42.1	421	0.57
2775	0.54	0	0.15	0.39	0.28	72.2	445	0.54
2785	0.5	0	0.2	0.39	0.34	78	431	0.59
2830	0.74	0	0.12	0.36	0.25	48.6	428	0.48
2840	0.9	0	0.17	0.38	0.31	42.2	431	0.55
2847	0.8	0	0.19	0.33	0.37	41.3	427	0.52
2854	0.59	0	0.14	0.39	0.26	66.1	429	0.53
2907	0.55	0	0.16	0.18	0.47	32.7	416	0.34
2949	0.59	0	0.05	0.22	0.19	37.3	428	0.27
2979	0.59	0	0.08	0.28	0.22	47.5	436	0.36
3009	0.52	0	0.06	0.22	0.21	42.3	433	0.28
3099	0.59	0	0.05	0.29	0.15	49.2	430	0.34
3189	0.67	0	0.03	0.31	0.09	46.3	431	0.34
3249	0.81	0.01	0.05	0.37	0.12	45.7	426	0.43
3256	7.91	0.12	2.46	24.61	0.09	311.1	442	27.19
3257	1.72	0.03	0.35	2.86	0.11	166.3	449	3.24
3258	1.62	0.03	0.39	2.42	0.14	149.4	442	2.84
3259	3.24	0.02	0.59	6.11	0.09	188.6	445	6.72
3266	6.97	0.11	1.59	17.66	0.08	253.4	442	19.36
3269	2.45	0.04	0.62	5.44	0.1	222	449	6.1
3270	20.8	0.18	8.35	66.08	0.11	317.7	443	74.61
3271	77.6	0.43	47.8	290.1	0.14	373.8	439	338.33
3339	0.76	0.01	0.06	0.33	0.15	43.4	437	0.4
3384	0.77	0.02	0.24	0.83	0.22	107.8	450	1.09
3393	10.4	0.29	1.74	23.41	0.07	225.1	433	25.44
3432	1.42	0.1	0.27	1.81	0.12	127.5	440	2.18
3459	1.5	0.15	0.33	1.8	0.14	120	441	2.28
3489	0.95	0.01	0.09	0.56	0.14	58.9	438	0.66
3516	1.76	0.15	0.34	2.71	0.13	154	442	3.2
3579	0.84	0	0.11	0.42	0.21	50	430	0.53
3639	0.9	0.01	0.16	0.53	0.23	58.9	432	0.7
3699	0.96	0.01	0.09	0.62	0.13	64.6	440	0.72
3759	0.93	0.01	0.11	0.65	0.14	69.9	433	0.77
3819	0.85	0	0.1	0.46	0.18	54.1	425	0.56
3849	0.86	0	0.12	0.43	0.22	50	437	0.55
3879	0.79	0	0.14	0.55	0.2	69.6	437	0.69
3885	0.71	0	0.1	0.33	0.23	46.5	436	0.43
Max.	77.6	0.43	47.8	290.1	0.47	373.8	450	338.33
Min.	0.5	0	0.03	0.18	0.07	32.7	416	0.27
Average	5.09	0.04	2.52	16.00	0.20	116.40	434.38	18.57

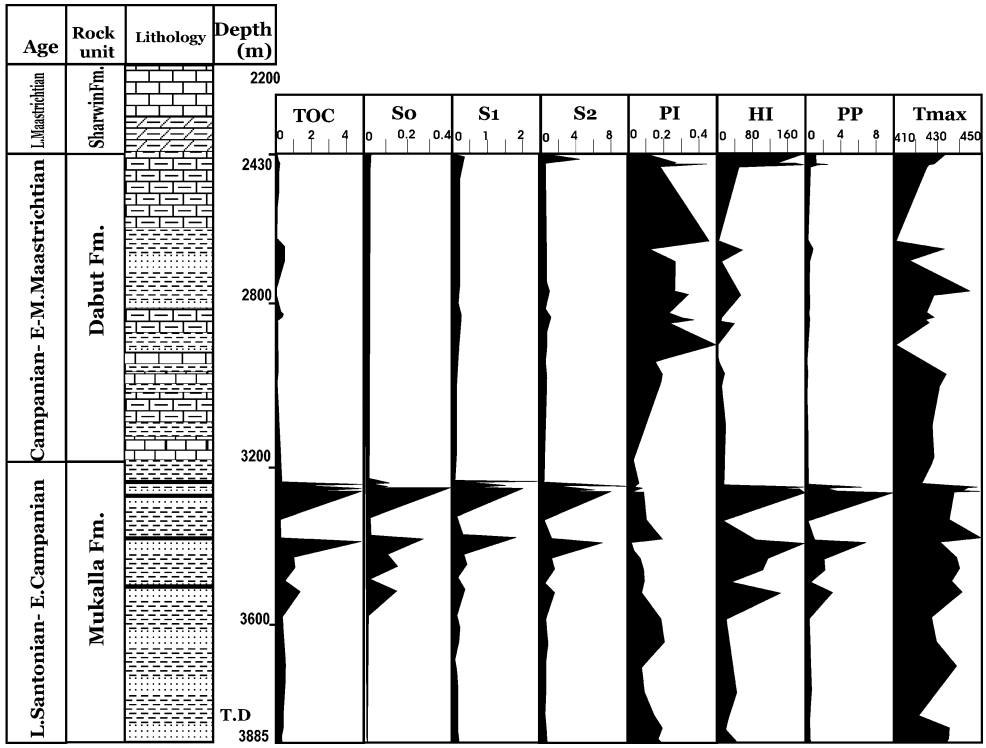

Fig. 2 Organic geochemical log of the studied samples of the Mukalla and Dabut Formations of 16/G-1 offshore well

The TOC is expressed as the relative dry weight percentage of organic carbon in the sediments (Batten 1996a, b), but not a direct measure of the total amount of organic matter. It is generally accepted that for a rock to be a source of hydrocarbons, must contain sufficient organic matter for significant generation and expulsion for many years; this was taken as 0.5 wt.% TOC for shales and somewhat less 0.3 wt.% TOC for carbonates (Batten 1996b). The minimum TOC content of a source rock needs to be within the range of 1–2 wt.% (Peters and Cassa 1994). Samples of the Mukalla and Dabut Formations have the moderate to high TOC contents especially of Mukalla within the depth intervals between 3,250 and 3,700 m. TOC ranges from 0.5 to 77.6 wt.% and have a median of 5.09 wt.% (Table 1). The highest TOC values 7.9, 7, 20.8, 77.6 and 10.4 wt.% at depth intervals of 3256, 3266, 3270, 3271, and 3393 m, respectively, which related to coal layers and laminae. Twenty-one samples of Dabut Formation with values 0.5–0.95 wt.% TOC, 0.18–1.51 mg/g S_2 and 416–445°C T_{max} represents low to moderate petroleum potentiality and maturity (Table 1; Figs. 3 and 4). Twenty-four samples of Mukalla Formation with values ranging between 0.76 and 77.6 wt.% TOC, 0.33–290.1 mg/g S_2, and 426–450°C T_{max} (Table 1; Figs. 3 and 4).

Kerogen types

Figures 3 and 5 show a modified Van Krevelen diagram with kerogen types, petroleum potentiality as well as the maturation stages of studied samples of 16/G-1 offshore well. The organic geochemical results of the Mukalla and Dabut Formations showed the maturation stage and petroleum potentiality. Most of the obtained kerogen types are type II and III, which fits with the predominance of oil and gas prone source rock potentiality.

Espitalie et al. (1984) suggested the oil show analysis, which measures the free gas in the rock (S_0), the free oil in rock (S_1), the hydrocarbons from cracking kerogen (S_2), and the CO_2 formed by oxidation of the residual carbon (S_4). The total organic carbons (TOC wt.%) was calculated as the sum of the pyrolyzed and residual organic carbons. The S_3 for calculating OI is replaced by the S_4 for calculating TOC. The kerogen quality and maturity are determined by plotting HI versus T_{max} rather than HI versus OI (Fig. 4). This eliminates the use of OI as a kerogen type indicator (comparable to the O/C in the Van Krevelen diagram). The kerogen type designations are based entirely on the HI (Hunt 1996). The interpretation of maturation, however, is somewhat improved with the HI–T_{max} plot. Figure 4 shows an HI versus T_{max} plot for the samples of the studied well, most studied samples are mature, especially those of Mukalla Formation which are in the mature petroleum generating range (430 to 465°C). Some samples of the Dabut Formation are late immature; and most of them are mature (Fig. 4).

The kerogen type can be established by pyrolysis and by optical palynological methods. The cross plotting of the hydrogen index and other parameters is used to indicate to the kerogen type or/and maturation stage, so-called modified Van Krevelen diagram, or HI versus (T_{max}), temperature at which the maximum generation of the

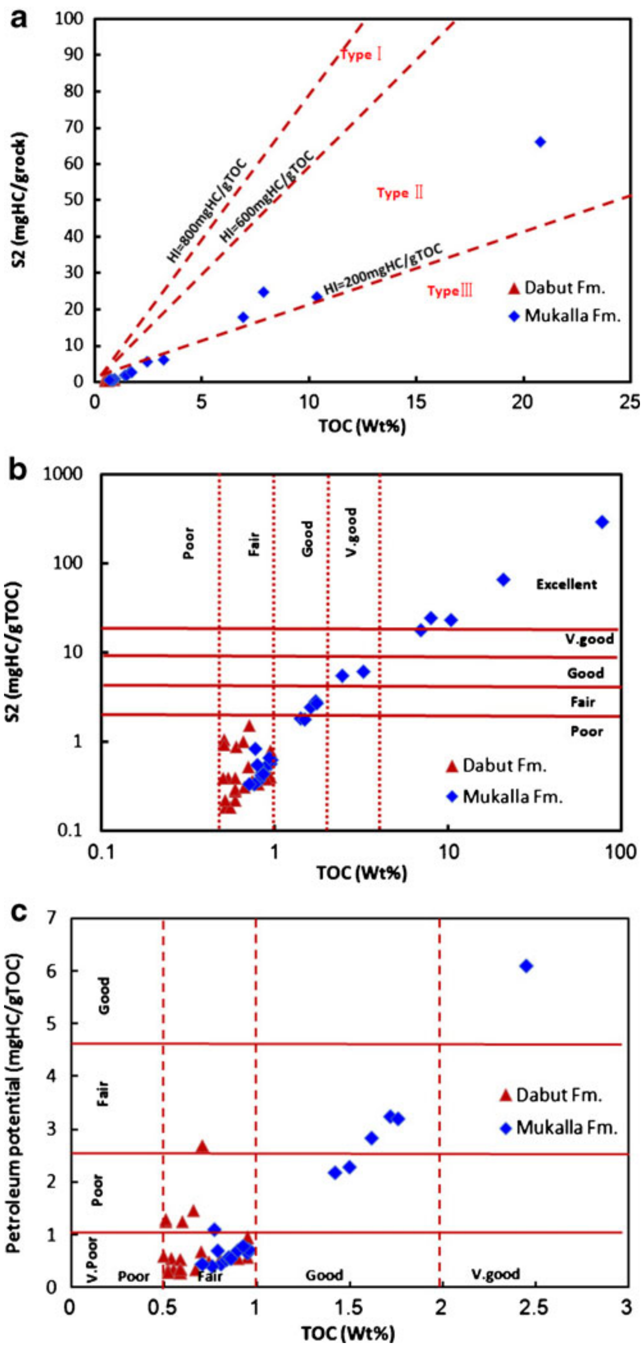

Fig. 3 **a** Plot of TOC wt.% versus S_2 mg HC/g rock indicating the kerogen types. **b** Plot of (TOC wt.%) versus (S_2, mg HC/g rock) indicated hydrocarbon potentiality and source rock efficiency; most samples found to be fair to excellent. **c** TOC and PP plot shows the source rock generative potential and hydrocarbon potentiality

products of pyrolysis occurs (Fig. 4a–b). The studied samples in this well are late immature stage in upper part of the Dabut Formation and down to 3200 m depth, based on T_{max} pyrolysis parameter. The second interval of the studied well "mainly of Mukalla Formation" is mature with moderate to low HI and moderate to high TOC values of the Mukalla intervals, indicated a good source rock that should be evaluated where it is more mature (Figs. 2, 3, and 4).

The production index PI ($S_1/S_0+S_1+S_2$), typically climbs from 0.1 to 0.4 particularly from the beginning to the end of the oil-generation window (Hunt 1996). Most PI values of studied samples are evaluated to be in this range of oil-generation window with average value (0.2), maximum value (0.47) and minimum value (0.07; Table 1; Figs. 2, 3c and 4c).

In our study, the optical method are used to determine organic composition by using the transmitted light microscopic investigation of the Mukalla and Dabut Formations indicate that the occurrence of higher amounts of the various types of sedimentary organic matter with the dominancy of mixed marine kerogen type II and terrestrial kerogen type III.

Maturation and paleothermal indicators

Several data types and parameters are used to evaluate the level of organic maturity; these include TAI, R_0, rock-eval pyrolysis–T_{max} parameter (Killops and Killops 1993, 1995; Hunt 1996; Peters et al. 2005). The top and bottom of the oil and gas generation varies with the type of organic matter, ranging from 0.5–1.0% R_0 and 1.4–3.5% R_0, respectively (Tissot and Welte 1984; Espitalié et al. 1984).

Thermogenic oil is thought to be generated at vitrinite reflectance values above 0.6% R_0 for kerogen type I and II (Bordenave 1993). The lowest value of vitrinite reflectance association with the known generation of conventional oil is about 0.5% and 0.6% generally recognized as the beginning of commercial oil accumulations. The peak of oil-generation with vitrinite reflectance values lies around 0.8 to 1% R_0. At higher vitrinite reflectance levels, the gas/oil ratios increase rapidly with vitrinite reflectance values. Most samples of the studied section are less than 1% R_0 except for two samples which give higher reading with values 1.75% R_0 and 1.03% R_0 of 2499 m and 3789 m sample depth. The minimum reading of studied samples is 0.52 R_0, so the most studied samples are within the range of the oil window or fit to the peak of the oil window and wet gas generation zone (Table 2 and Figs. 5 and 6). Thermal maturity of organic matter was estimated by T_{max} (temperature maximum of S_2), and PI from rock-eval pyrolysis analysis. According to Tissot and Welte (1984), the zone of oil-generation ranges between T_{max} temperatures of 435 and 460°C and between PI values of 0.1 and 0.4. T_{max} and PI data are listed in Table 1. T_{max} is considered here to be most reliable when derived from samples where S_2 equals 0.4 mg HC/g rock, whereas PI is considered most reliable when derived from samples having TOC 0.5 wt.% (Table 1; Fig. 4).

Generally, the vitrinite reflectance values increase with depth due to the gradual increase in temperature and also in the age. The mean random R_0 values for all samples reported

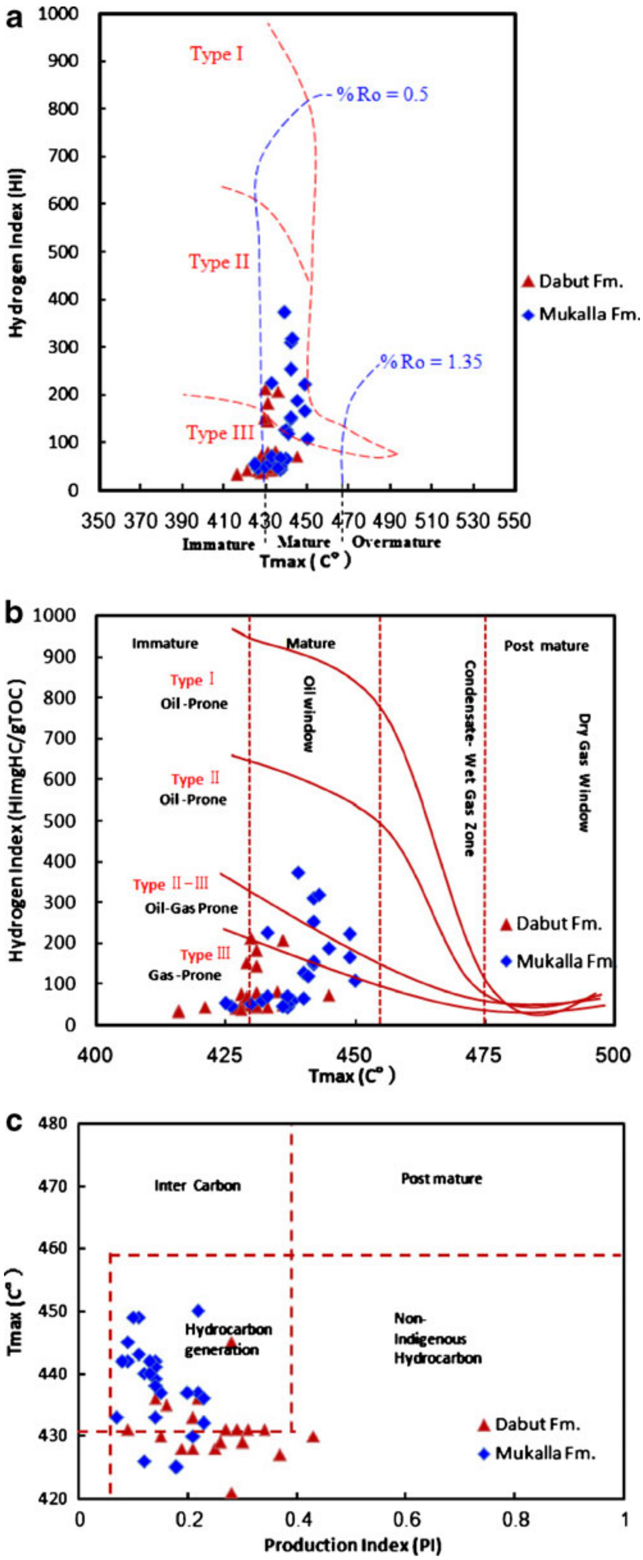

Fig. 4 **a-b** T_{max} and HI plot explaining the relations of kerogen types and maturation stages with petroleum generation potentiality. Most samples plot lie in the area of oil window and mature zone with kerogen type II and III. **c** Production index (PI) versus (T_{max} °C) plot, shows and indicates hydrocarbon generation zone. Most samples are within hydrocarbon generation zone

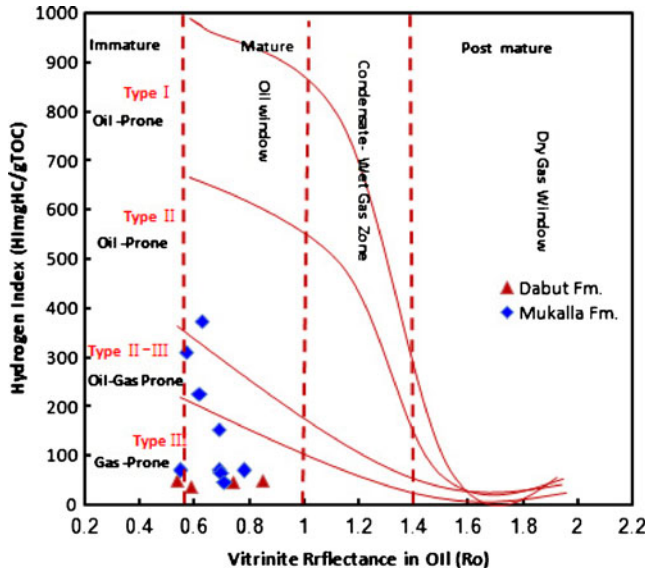

Fig. 5 Vitrinite reflectance (R_0) versus hydrogen index (HI) plot to explain the relations maturation stages and kerogen types with petroleum generation potentiality. Most samples can produce oil and gas

herein ranges from 0.52 to 1.75%. These R_0 values indicate a thermal maturity level from late immature to mid mature stage oil/early gas generation with respect to oil and gas potential (Table 2 and Fig. 5b). T_{max} values range from 416 to 450°C and correlate well with measured R_0 indicating their reliable maturity indicator to mature stage with oil/gas prone, and confirm that the analyzed samples are in the oil window which is approximately 0.6–1.2% R_0 (Tissot and Welte 1984; Hunt 1996). HI values are low in most Dabut Formation and the lower part of the Mukalla Formation compared with those of the upper part of Mukalla Formation (Table 1). Figure 5 shows HI versus T_{max} or R_0 plots close to the kerogen Type II and Type III of organic matter maturation pathway of Espitalié (1985). Whereas HI values (120–373) are much higher in the upper part samples of the Mukalla Formation. The distribution of R_0 values suggest that most of Mukalla argillaceous, calcareous shale, coal layers and shale samples are sufficiently mature to generate oil and gas (Table 2; Fig. 5).

The thermal maturity of organic matter in the analyzed samples is also evaluated based on the T_{max} of the pyrolysis S_2 peak (Figs. 4 and 6). The maturation range of T_{max} was found to be varied for different types of organic matter (Tissot and Welte 1984; Peters 1986; Bordenave 1993). T_{max} is narrow for kerogen Type I but is wider for Type II and much wider for Type III due to the increasing structural complexity of the organic matter (Tissot et al. 1987). The maturation window for oil/condensate generation from Type I and II organic matter ranges from 430 to 470°C

Table 2 Vitrinite reflectance data of 16/G-1 offshore well

Depth (m)	2468	2499	2679	2739	2830	2859	2899	2949	2979	3039	3069	3159
R_0	0.54	1.75	0.52	0.53	0.54	0.56	0.76	0.59	0.85	0.59	0.75	0.56
Read. no.	1	14	30	39	39	18	7	11	3	8	2	25
Depth (m)	3189	3256	3271	3393	3516	3579	3609	3699	3759	3789	3879	3885
R_0	0.74	0.57	0.63	0.62	0.69	0.69	0.98	0.7	0.78	1.03	0.55	0.71
Read. no.	5	50	50	50	50	47	3	50	23	7	8	30

and for dry gas generation more than 470°C (Tissot et al. 1987; Peters 1986). The oil window for Type III terrigenous organic matter ranges from 465 to 470°C, while the condensate/wet gas window corresponds to T_{max} up to 540°C (Bordenave 1993). Figure 3 shows the HI versus T_{max} plot for the studied samples particularly those of the Mukalla Formation are in the mature petroleum generating range (430 to 465°C) on the other hand the samples of Dabut Formation are late immature and only few ones are early mature. Most kerogens of the Mukalla and Dabut samples are of type II and type III, which fits with the predominance of oil and gas prone source rocks. The pyrolysis T_{max} values for the studied samples (416–450°C)

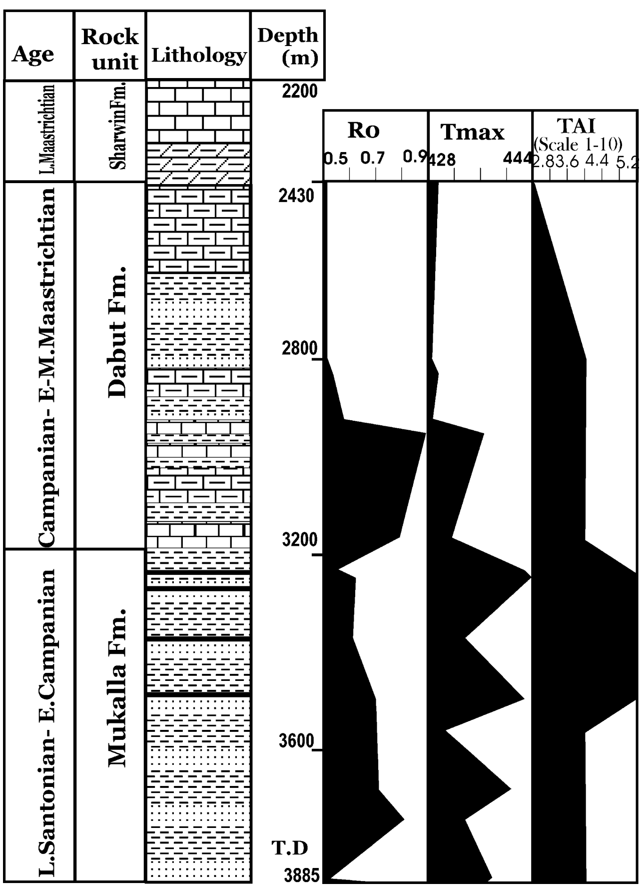

Fig. 6 Paleothermal indicators R_0, T_{max} and TAI versus depth of 16/G-1 offshore well

indicate that the Mukalla and Dabut Formations are latest immature to mature stage (Tables 1, 2, and 3). The three paleothermal indicators are used in this study (R_0, T_{max}, and TAI), which indicate latest diagenesis and catagenesis maturation stages of the studied samples (Fig. 6).

Figure 6 shows no variation between the three types of paleothermal indicators of T_{max}, TAI, and R_0 as they are compatible and indicate that the maturation is increased with the increasing depth.

Several numerical scales, based on palynomorphs colors and linked with phases of organic maturation and petroleum generation, were erected in the late 1960s (Staplin 1969). The TAI was developed as a relatively simple and rapid technique for evaluating kerogen maturation in direct well cuttings from the change in color that reflects the thermal and burial history of the organic matter. TAI, in general, as a numerical scale is based on thermally induced color changes in spore and pollen with depth (Pearson 1984; Peters and Cassa 1994). The standard palynological processing technique was taken for 131 cutting and core samples without any oxidation treatments to eliminate the partial loss of color (Table 3). The current TAI scale (1–10) was widely used as an exploration tool with other maturation indicators, as shown in Fig. 6.

Deltoidospora/*Cyathidites* group is used to measure the TAI in most studied samples of the studied well (Table 3). Barnard et al. (1976) developed the spore coloration index (SCI) on a 1 to 10 scale specifically for spores. Both the Barnard et al. and Staplin scales are used as standard set of about 20 color slides. Smith (1983) correlated the color index scales of TAI and SCI. Then he put the spectra of a reference set of color slides for theses scales in a computer to be matched with new sample data. Other coloration scales such as TAI of Pearson (1984) and SCI of Collins (1990) are used to estimate the maturation of sedimentary organic matter. Rank assessment of sporomorphs under transmitted light is expressed as a TAI, from 1 to 4 or 5 after Pearson (1984). TAI (1–10 scale) as follows: TAI equal 1 to 3 is for immature stage (up to 0.5% R_0), TAI equal 4 to 7 (0.5–2% R_0) is for mature stage, and TAI equal 8 to 10 for overmature stage (≥2.5% R_0).

TAI with scale 1 to 10 are used in this study and most of the samples of the studied sections display gradual

Table 3 Sedimentary organic matter, palynological quantity, preservation and TAI of 16/G-1 well

S No	Depth (m)	Sm. type	Palyn. status	Pres.	TAI	Palyno.	Poll.	Spore	Din.	FLT	Alg.	Phyt.	AOM	Acrt.	Fungi	Tot.
1	2430	Cutting	Prod.	Fair	3	10	7	1	0	1	0	80	110	0	1	200
2	2435.5	Core	Fair	Fair	3	0	0	0	0	0	0	60	140	0	0	200
3	2436.1	Core	Fair	Non	3	0	0	0	0	0	0	30	140	0	0	170
4	2436.9	Core	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
5	2536.9	Core	Prod.	Fair	3	0	0	0	0	0	0	60	140	0	0	200
6	2437	Core	Prod.	Fair	3	0	0	0	0	0	0	30	120	0	0	150
7	2459.5	Core	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
8	2460	Core	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
9	2460.1	Core	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
10	2461.5	Core	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
11	2463.3	Core	Fair	Fair	3	0	0	0	0	0	0	10	100	0	0	110
12	2464.1	Core	Prod.	V.Good	3	267	4	0	230	30	3	10	100	0	0	377
13	2464.5	Core	Prod.	Good	3	8	3	2	0	0	3	42	150	0	0	200
14	2464.9	Core	Fair	Fair	3	0	0	0	0	0	0	30	170	0	0	200
15	2562	Cutting	Barren	Non	3	0	0	0	0	0	0	0	0	0	0	0
16	2577	Cutting	Fair	Fair	3	5	1	0	3	1	0	50	145	0	0	200
17	2598	Cutting	Fair	Fair	3	10	0	0	4	4	1	20	170	0	1	200
18	2610	Cutting	Fair	Fair	3	0	0	0	0	7	0	25	168	0	0	200
19	2631	Cutting	Prod.	Fair	3	210	113	58	15	17	6	60	30	0	1	300
20	2634	Cutting	Prod.	Fair	3	37	21	2	1	3	0	110	63	10	0	210
21	2640	Cutting	Prod.	Good	3	138	80	30	15	7	2	60	30	3	1	228
22	2646	Cutting	Prod.	Good	3	70	36	12	5	12	1	40	90	3	1	200
23	2652	Cutting	Fair	Fair	3	12	10	2	0	0	0	100	88	0	0	200
24	2658	Cutting	Fair	Fair	3	24	22	2	0	0	0	80	90	0	0	194
25	2670	Cutting	Fair	Fair	3	25	10	12	3	0	0	100	88	0	0	213
26	2682	Cutting	Fair	Fair	3	14	10	2	0	2	0	95	88	0	0	197
27	2694	Cutting	Fair	Fair	3	16	14	2	0	0	0	100	88	0	0	204
28	2714	Cutting	Fair	Fair	3	12	10	2	0	0	0	90	88	0	0	190
29	2745	Cutting	Barren	Non	no	0	0	0	0	0	0	0	0	0	0	0
30	2760	Cutting	Prod.	Good	3	72	35	26	3	5	2	70	60	0	0	201
31	2775	Cutting	Prod.	Good	4	65	26	20	6	9	2	65	70	1	1	200
32	2790	Cutting	Prod.	Good	3	79	35	22	8	11	1	60	61	1	1	200
33	2799	Cutting	Prod.	Good	3	18	12	6	0	0	0	100	82	0		200
34	2811	Cutting	Prod.	Good	4	48	30	10	2	3	1	120	50	1	1	218
35	2823	Cutting	Prod.	Good	4	86	44	20	8	6	3	60	54	3	2	200
36	2835	Cutting	Prod.	Good	4	69	35	25	2	4	1	80	55	1	1	204
37	2850	Cutting	Prod.	Good	4	84	45	30	0	0	5	80	36	0	4	200
38	2868	Cutting	Prod.	Good	4	76	40	25	2	3	4	64	60	1	1	200
39	2883	Cutting	Prod.	Good	4	70	30	20	4	5	7	70	60	2	2	200
40	2898	Cutting	Prod.	Good	4	50	25	20	1	1	2	75	75	0	1	200
41	2910	Cutting	Prod.	Good	4	40	30	3	1	2	3	80	80	0	1	200
42	2925	Cutting	Prod.	Good	4	37	25	10	1	1	0	90	73	0	0	200
43	2949	Cutting	Prod.	Good	4	74	20	10	15	20	5	56	70	2	2	200
44	2964	Cutting	Prod.	Good	4	45	30	10	1	1	1	85	70	1	1	200
45	2982	Cutting	Prod.	Good	4	58	24	22	5	4	1	72	70	1	1	200
46	2985	Cutting	Prod.	Good	4	81	40	25	5	6	2	90	29	2	1	200
47	3000	Cutting	Barren	Good	4	77	42	30	1	1	1	80	45	1	1	202
48	3006	Cutting	Barren	Good	4	47	20	14	5	5	1	75	78	1	1	200
49	3018	Cutting	Barren	Good	4	44	30	11	1	1	1	61	95	0	0	200

Table 3 (continued)

S No	Depth (m)	Sm. type	Palyn. status	Pres.	TAI	Palyno.	Poll.	Spore	Din.	FLT	Alg.	Phyt.	AOM	Acrt.	Fungi	Tot.
50	3033	Cutting	Prod.	Good	4	49	25	20	2	2	0	80	71	0	0	200
51	3048	Cutting	Prod.	Good	4	49	30	12	2	2	1	81	70	1	1	200
52	3063	Cutting	Prod.	Good	4	51	40	2	4	4	1	75	75	0	0	201
53	3075	Cutting	Prod.	Good	4	56	30	20	2	2	2	74	70	0	0	200
54	3087	Cutting	Prod.	Good	4	52	25	15	8	1	1	75	73	1	1	200
55	3090	Cutting	Prod.	Good	4	35	18	11	4	1	1	80	85	0	0	200
65	3105	Cutting	Prod.	Good	4	63	30	20	8	4	1	70	67	0	0	200
57	3126	Cutting	Prod.	Good	4	84	40	20	12	9	1	60	65	1	1	209
58	3141	Cutting	Prod.	Good	4	82	32	22	15	11	2	80	90	0	0	252
59	3156	Cutting	Prod.	Good	4	30	10	4	4	11	1	70	100	0	0	200
60	3177	Cutting	Prod.	Good	4	245	31	30	64	103	5	50	50	9	3	345
61	3185	Cutting	Prod.	Good	4	60	11	12	12	20	3	50	90	1	1	200
62	3198	Cutting	Prod.	Good	4	144	27	25	50	27	11	30	50	3	1	224
63	3201	Cutting	Prod.	Good	4	211	40	37	60	68	1	50	40	3	2	301
64	3210	Cutting	Prod.	Good	4	41	22	3	8	7	1	70	100	0	0	211
65	3213	Cutting	Prod.	Good	4	25	18	1	3	3	0	90	85	0	0	200
66	3222	Cutting	Prod.	Good	4	28	13	7	4	1	1	110	62	0	2	200
67	3228	Cutting	Fair	Fair	4	0	0	0	0	0	0	80	120	0	0	200
68	3230	Cutting	Prod.	Good	4	42	9	6	13	8	6	60	100	0	0	202
69	3240	Cutting	Prod.	Fair	4	20	12	1	6	1	0	70	110	0	0	200
70	3255	Cutting	Prod.	Fair	5	5	5	0	0	0	0	70	125	0	0	200
71	3267.5	Core	Barren	Non	no	0	0	0	0	0	0	0	0	0	0	0
72	3267.8	Core	Barren	Non	no	0	0	0	0	0	0	0	0	0	0	0
73	3267.8	Core	Fair	Fair	5	0	0	0	0	0	0	30	170	0	0	200
74	3268.2	Core	Barren	Non	no	0	0	0	0	0	0	0	0	0	0	0
75	3268.8	Core	Prod.	Fair	5	10	7	3	0	0	0	100	90	0	0	200
76	3270.6	Core	Prod.	Fair	5	0	0	0	0	0	0	150	50	0	0	200
77	3271.1	Core	Prod.	Fair	5	0	0	0	0	0	0	20	180	0	0	200
78	3271.9	Core	Barren	Non	no	0	0	0	0	0	0	0	0	0	0	0
79	3279	Cutting	Prod.	Fair	5	32	15	2	7	1	6	80	120	1	0	232
80	3297	Cutting	Prod.	Fair	5	6	6	0	0	0	0	64	130	0	0	200
81	3306	Cutting	Prod.	Good	5	103	36	29	22	10	6	100	50	0	0	253
82	3321	Cutting	Prod.	Good	5	0	0	0	0	0	0	80	120	0	0	200
83	3324	Cutting	Prod.	V.Good	5	144	54	27	39	13	7	60	40	2	2	244
84	3330	Cutting	Prod.	V.Good	5	209	76	40	61	14	14	80	20	1	3	309
85	3339	Cutting	Prod.	V.Good	5	25	11	2	3	8	1	80	95	0	0	200
86	3348	Cutting	Prod.	V.Good	5	171	72	31	38	10	12	80	32	3	5	283
87	3360	Cutting	Prod.	V.Good	5	30	15	6	6	2	1	80	90	0	0	200
88	3366	Cutting	Prod.	Good	4	35	20	18	7	1	6	20	126	2	0	200
89	3375	Cutting	Prod.	V.Good	4	133	41	40	32	5	6	50	70	8	1	253
90	3381	Cutting	Prod.	Good	5	106	30	20	33	15	1	40	60	1	0	200
91	3393	Cutting	Prod.	Good	4	44	10	7	10	16	1	90	66	0	0	200
92	3396	Cutting	Prod.	V.Good	4	41	12	8	9	8	4	79	80	0	0	200
93	3405	Cutting	Prod.	Good	5	45	19	9	7	3	7	75	80	0	0	200
94	3414	Cutting	Prod.	V.Good	5	153	37	35	9	3	67	25	23	0	1	200
95	3423	Cutting	Prod.	V.Good	5	63	15	8	1	1	38	70	67	0	0	200
96	3432	Cutting	Prod.	V.Good	5	203	66	32	62	11	26	47	50	5	1	300
97	3441	Cutting	Prod.	V.Good	5	222	81	47	42	6	60	20	48	3	1	308
98	3456	Cutting	Prod.	V.Good	5	85	32	17	8	6	20	70	45	1	1	200

Table 3 (continued)

S No	Depth (m)	Sm. type	Palyn. status	Pres.	TAI	Palyno.	Poll.	Spore	Din.	FLT	Alg.	Phyt.	AOM	Acrt.	Fungi	Tot.
99	3465	Cutting	Prod.	V.Good	5	124	42	35	28	7	8	30	46	3	1	200
100	3471	Cutting	Prod.	V.Good	5	47	19	8	11	0	9	60	93	0	0	200
101	3483	Cutting	Prod.	V.Good	5	26	10	10	2	2	2	110	64	0	0	200
102	3489	Cutting	Prod.	V.Good	5	39	23	9	5	1	1	91	70	0	0	200
103	3504	Cutting	Prod.	V.Good	5	37	22	8	5	1	1	90	73	0	0	200
104	3522	Cutting	Prod.	V.Good	5	36	21	7	5	1	1	85	79	1	0	200
105	3537	Cutting	Prod.	V.Good	4	33	20	7	4	1	1	85	82	0	0	200
106	3546	Cutting	Prod.	V.Good	4	50	30	12	3	2	1	90	60	1	1	200
107	3561	Cutting	Prod.	V.Good	4	63	35	16	8	4	0	70	67	0	0	200
108	3576	Cutting	Prod.	V.Good	4	71	37	20	11	3	0	70	59	0	0	200
109	3591	Cutting	Prod.	V.Good	4	79	36	26	15	2	0	75	46	0	0	200
110	3606	Cutting	Prod.	V.Good	4	87	40	25	20	2	0	80	33	0	0	200
111	3630	Cutting	Prod.	V.Good	4	92	40	26	19	4	1	70	38	1	1	200
112	3645	Cutting	Prod.	V.Good	4	104	45	30	20	5	2	65	31	1	1	200
113	3657	Cutting	Prod.	V.Good	4	121	48	36	25	7	2	60	40	2	1	221
114	3675	Cutting	Prod.	V.Good	4	174	28	30	9	1	103	40	20	2	1	234
115	3687	Cutting	Prod.	Fair	4	50	10	24	5	3	6	100	50	1	1	200
116	3699	Cutting	Prod.	V.Good	4	98	21	31	36	3	4	72	30	1	2	200
117	3705	Cutting	Prod.	V.Good	4	170	43	47	64	4	3	60	30	1	8	260
118	3714	Cutting	Prod.	V.Good	4	121	20	30	55	12	4	49	30	0	0	200
119	3723	Cutting	Prod.	V.Good	4	90	29	42	12	2	2	70	40	2	1	200
120	3732	Cutting	Prod.	V.Good	4	143	52	44	21	14	9	60	40	2	1	243
121	3750	Cutting	Prod.	V.Good	4	88	23	29	15	8	9	70	42	2	2	200
122	3768	Cutting	Prod.	V.Good	4	135	32	44	30	14	12	80	40	2	1	255
123	3777	Cutting	Prod.	Fair	4	108	32	45	13	12	2	110	30	2	2	248
124	3780	Cutting	Prod.	V.Good	4	127	31	42	33	5	4	120	40	9	3	287
125	3783	Cutting	Prod.	V.Good	4	44	20	10	4	4	2	86	70	4	0	200
126	3795	Cutting	Prod.	Good	4	72	36	19	8	7	2	75	53	0	0	200
127	3813	Cutting	Prod.	Good	4	101	30	27	26	6	4	30	69	1	7	200
128	3831	Cutting	Prod.	V.Good	4	83	26	14	16	10	4	60	60	1	12	203
129	3852	Cutting	Prod.	V.Good	4	161	40	60	30	16	15	60	50	0	0	271
130	3870	Cutting	Prod.	V.Good	4	118	49	46	31	9	7	70	20	7	9	248
131	3885	Cutting	Prod.	V.Good	4	182	81	30	40	14	8	70	40	4	5	292

increasing in color with increasing depth. The color ranges from dark yellow to orange–brown (Table 3; Fig. 6). Estimates of TAI as maturity indicator by using the most abundant genera in studied sections *Deltoidospora*/*Cyathidites* Group, or by using the color of rounded pollen grains are available if the *Deltoidospora*/*Cyathidites* Group are not represented in sample. The samples of the upper part of Dabut Formation with the dark yellow dominant color of 3 of 10 TAI scale values for depth interval 2,300–2,800 m. The predominant color of this upper part of the Dabut Formation indicates late diagenesis to early catagenesis stages of maturation. The predominance of orange color is characterizes the lower part of Dabut Formation with 4 of 10 TAI scale values for depth interval 2,811–3,200 m, that representing of early catagenesis stage of maturation. The Mukalla Formation is characterizing by orange to brown predominance color with increasing of burial depth from 3,200 to 3,885 m. TAI values are range from 4 to 5 of a 10-point scale. These measurements indicate an early to middle catagenesis stage of maturation (Table 3, Fig. 6).

Petroleum potentiality

The TOC in sediments generally indicate to the quantity of kerogen in the rock. Other indications of organic content are thermal cracking of the organic matter by pyrolysis as results of S_1 (mg/g) that views the existing petroleum content and S_2 (mg/g) as the remaining petroleum generating potential of kerogen in the rock (Peters 1986; Hunt 1996). High S_1 values may indicate effective source rocks or rocks containing migrated oil while S_2 is more realistic measure of source rock potential than TOC because TOC include "dead carbon" which incapable of generating petroleum. According to Langford and Blanc-Valleron (1990), plots of S_2 versus TOC eliminate the problems caused by matrix effects, and also give a better evaluation of present-day hydrocarbon generating potential than normal HI/OI plots (Fig. 4b). Similarly, plots of petroleum potentiality $(S_1 + S_2 = \mathrm{PP})$ with TOC are also used to estimate potential S_2 and effective S_1 hydrocarbon producing capacity with minimizing effects (Fig. 4a).

The organic geochemical data represents sufficient organic matter which is preserved within the Mukalla and Dabut Formations to qualify them as potential source rocks for hydrocarbons generation (Table 1). Most of the samples analyzed having TOC values greater than the critical lower limit range (0.5 wt.%) cited by different authors (Tissot and Welte 1984; Hunt 1996).

Plotting of the petroleum potentiality PP (S_0+S_1+S_2) versus TOC content on Tissot and Welte (1984) diagram (Fig. 3c) indicate that the highest hydrocarbon generation pertain to the Mukalla Formation as a main source rocks, with mainly high total organic carbon content of 0.7 to 77.6 wt.% and good petroleum potential of 0.43–338 kg HC/ton rocks. On the other hand, plotting the pyrolysis analysis of the studied samples determined hydrogen index HI (S_2/TOC×100) with maximum temperature for hydrocarbon pulse the pyrolysis ($T_{\max}$) and Van Krevelen diagram of Espitalie et al. (1984; Fig. 4a, b). Most of the samples indicate that the Mukalla Formation represents the main source rock with kerogen types II and III. The studied samples of the Mukalla Formation are characterized by mature organic matter content with 425–450°C $T_{\max}$ and HI up to 373 mg HC/g rock. On the other hand the studied samples of Dabut Formation are mostly of Kerogen type III and mainly late immature to early mature stages with 416–436°C $T_{\max}$ and HI up to 207 mg HC/g rock. Therefore, it is appropriate to suggest from this diagram that the Mukalla Formation has the higher hydrocarbon generation than Dabut Formation.

Palynofacies assessments

Sedimentary organic matter and palynomorphs

Disseminated sedimentary organic matters (SOM) are mainly derived from aquatic and terrestrial sources such as algal, fungal, bacterial, microplanktons, miospores and other organic material products. These types of SOM have been distinguished and identified to evaluate the source rock by using transmitted light microscope (Thompson and Dembicki 1986). The different types of SOM have different hydrocarbon generation potential and products (Brooks 1981; Tissot and Welte 1984; Tyson 1995). The amount of hydrocarbons generated is controlled not only by the quantity and quality of the SOM but also by the level of maturity. Optical microscopy of the palynological slides from the Mukalla and Dabut Formations recorded in Table 3. The most of SOM of the studied samples are of dark yellow to orange or light brown color with good preservation conditions. The thermal alteration index being the same colors as 3 to 5 values (the used scale from one to ten "1–10" for comparison with other scales, see Batten 1996a,b. TAI are measured and recorded values of all studied samples according to this one to ten scale (Table 3; Fig. 6). Accordingly, they are mature and capable of generating oil and gas. The palynomorphs composition of lower part of the Mukalla Formation is characterized by common assemblage of marine palynomorphs as dinoflagellate cysts and foraminiferal test lining (FTL) with present to common land-derived palynomorphs as input within marine environment. However, in the upper part of the studied section, the marine dinoflagellate cyst becomes less abundant than lower part probably reflecting the progress of a marine regression. Near the top, with a depth of 2,464 m, they attain up to ca. 80% of *Spiniferites ramosus* acme zone and 20% of another marine dinoflagellate cyst and FTL.

In general, the studied section represents multi-cycles of transgressive and regressive events within syn-rift stage of Qamar Basin resulting deposition of the Mukalla and Dabut Formations with input of land-derived miospores, freshwater algae, phytoclasts and another organic matter (Fig. 8).

The most abundant dinoflagellate cysts assemblage is: *Cerodinium granulostriatum*, *P. infusorioides*, *S. ecchinoideum*, *Spiniferites*, *Cornoferia*, *Florentinia*, and *Andalusiella* which represent open marine environment. Pteridophytic spores include mainly forms related to ferns and water ferns (Ariadnaesporites). Hepatic spores such as *Zlivisporis blanensis* are present to common constituents. Gymnosperms mostly represented by inaperturate pollen of uncertain or possibly coniferous affinity. Angiospermous pollen is by far the most common and diverse type among the terrestrial palynomorphs input. The Palm province of: *Longapertites*, *Spinizonocolpites* and *Monocolpites* are dominant and indicate of humidity and warm conditions. Another miospores occur as common or minor elements as *Verrucosisporites*, *Cyathidites/Deltoidospora*, *Retimonocolpites*, *Grainisporites*, *Arecipites*, *Monosulcite*, *Cycadopites*, *Ctenolophonidites costatus*, *Echitriporites*, *Triplanosporites*, *Concavissimisporites*, *Tricolpites*, *Araucariacites/Inaperturopollenites*, and others.

Fungal palynomorphs are encountered but are rare in the studied sections particularly where the input is from terrestrial origin. Freshwater algae (*Pediastrum*) are common and constitute the high value of total palynomorph in some samples of the studied sections. *Pediastrum* is apparently most typical of hard water lakes and swamps with tropical and low salinity conditions, some authors suggest its absence or rarely although in bog waters (Tyson 1995). *Pediastrum* is common in some studied samples with other indicators of marine assemblages, may be as a result of its redeposition or transportation into the shelf and marine environments (Fig. 7).

Palynofacies types

The palynomorph and SOM are used to indicate palynofacies indicators of the depositional conditions and paleoenvironments. The potential of palynofacies studies as a tool in hydrodynamic and paleoenvironmental interpretations. The three main groups of constituents that form palynofacies display a significance variation, which includes of palynomorph, amorphous organic matter and phytoclasts. The palynomorph group includes the sporomorphs (miospores) subgroup (spores and pollen), the phytoplankton subgroup (dinoflagellate cysts and acritarchs) and the zoomorph subgroup (foraminiferal test lining and others). Petroleum palynologists, frequently analyze the group of amorphous organic matters (AOM), which used as evidence of depositional conditions at the site of accumulation and also records the diagenetic levels when studied by the geochemical methods. By contrast, the phytoclast group has received less attention, probably due to difficulties in attributing them to a precise biological producer. This group has limited biostratigraphical value and include of woods, cuticles, tissues, filaments and fungal hyphae. Most of macrophyte debris particles that constitute the phytoclasts group are hydrodynamically comparable to coarse silt or fine sand as well as the phytoclasts residues in their physical characteristics that are indicators of the current energy deposition and preservation (Tyson 1995).

Palynofacies studies are frequently devoted to palynomorphs, AOM, and phytoclasts based on Tyson's palynofacies concept of ternary palynomorphs–phytoclasts–AOM (PPA) and ternary microplanktons–pollen–spores (MPS) plots, which are used in this study. The Mukalla and Dabut Formations comprise a succession of nearshore to offshore marine-shelf conditions, with strong input from terrestrial material within this marine environment from northern parts to southern parts of the basin. The marine sites was deep enough to scatter basinal facies accumulation of suboxic–anoxic character, which is consisting of moderate ratio of the mixed marine inhibitors of dinoflagellates, foraminiferal lining test to the continental-derived spores and pollen. The Mukalla and

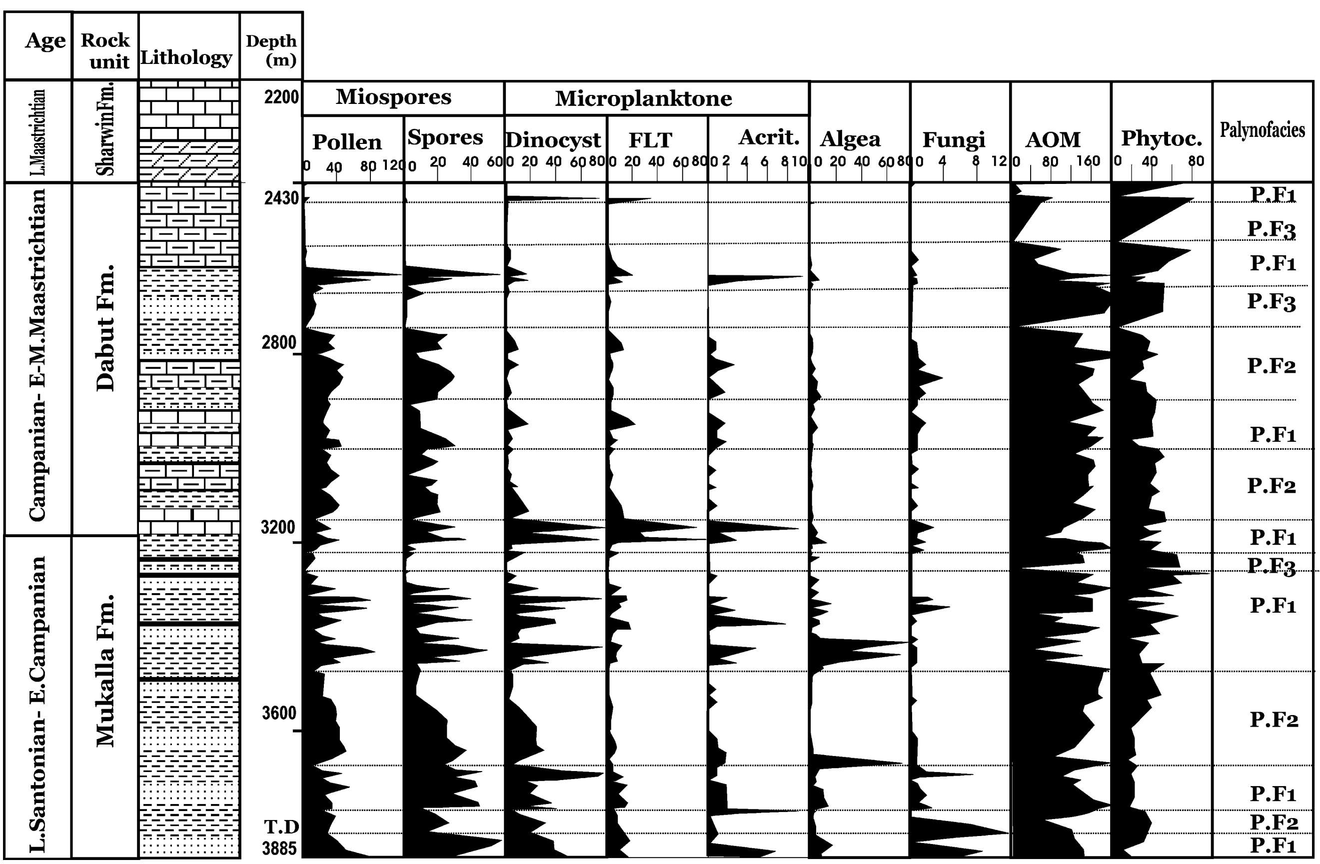

Fig. 7 Sedimentary organic matter (SOM), palynological components and Palynofacies of 16/G-1 offshore well

Dabut Formations were deposited in continuously subsiding basin events during break-up of southern Gondwana and separation of India and Madagascar in the Late Mesozoic (Brannan et al. 1997).

The quantitative analysis of the palynomorphs of marine and land-derived palynomorphs such as dinoflagellates, acritarchs, foraminiferal lining test, pollen, spores, algae and fungi was based on counting at least of 200 grains per sample. Actually, the number of the counted grains should be greater; however, the predominance of AOM results in counting of the palynomorphs and, in several cases, up to a dozen palynological slides per sample are required to obtain at least the number of 200 grains. Normal visual kerogen categorizes SOM particles as AOM; palynomorphs and phytoclasts (including all plants origin). The common Upper Cretaceous palynomorph species of spores and pollen grains that were derived from land plants, then dispersed by water and wind into the Mukalla and Dabut Formations shallow marine to open marine environments.

The common palynomorphs genera in these sediments are: *C. granulostriatum*, *Palaeohystrichophrus infusorioides*, *Spinidinium ecchinoideum*, *Spiniferites*, *Cornoferia*, *Florentinia* and *Andalusiella* of marine dinocysts. As well as miospores of land plants or terrestrial origin are: *Longapertites*, *Spinizonocolpites*, *Monocolpites*, *Z. blanensis*, *Ariadnaesporites*, *Verrucosisporites*, *Cyathidites*, *Deltoidospora*, *Retimonocolpites*, *Grainisporites*, *Arecipites*, *Monosulcite*, *Cycadopites*, *C. costatus*, *Echitriporites*, *Triplanosporites*, *Concavissimisporites*, *Tricolpites*, *Araucariacites*, *Inaperturopollenites*, and others.

The occurrence of the fresh water green algae *Pediastrum* in some samples of two formations are common. Fungal remains are orange to light brown color filamentous hyphae, spores, or mycelia of fungal origin, ranging in size from 10 μm to over 100 μm. They often coincide with the abundances of land plant debris. Wood particles are transparent, yellow or orange to pale brown and opaque to semi-opaque color, angular and equi-dimensional in shape and of moderate to small size. They may had been derived from land plant on coastal area, which are so small degradation or sometimes broken into moderate to small fragments during transportation from rivers and coastal areas in northern parts of the basin towards southern parts of it into the nearshore and offshore areas during deposition of the Mukalla and Dabut Formations (Figs. 1, 7, 8, and 9).

In conclusion, different vegetation zones may have been developed on paleocoastal line and inner parts of the northern and northwest parts of Qamar Basin under the influence of a warm-humid climate during the deposition of the Campanian/Maastrichtian sediments in the studied well (Fig. 1). A seaward Nypa mangrove zone existed succeeded landward by wet lowlands where bryophytes, pteridophytes, and palms thrived. Salvinealean water ferns and algae inhabited freshwater bodies. In the elevated hinterlands, Proteaceae and Coniferae may have grown.

The potential source rocks in the Qamar Basin shows that the Mukalla and Dabut Formations are characterized by very high percentages of well preserved orange to brown phytoclasts, amorphous organic matter, palynomorphs, and rare marine algae thereby the represents a mix of terrestrial and marine kerogen. The results indicate that two formations were deposited in open to a marginally shallow marine environments to proximal environment under bottom conditions that varied from anoxic to suboxic along a nearshore–offshore transect (Figs. 8 and 9).

The samples of Dabut Formation indicate deposition in a marginal to normal marine, distal shelf environment under anoxic to suboxic bottom environments. The Mukalla Formation was deposited in the open marine environment, relatively distal was setting under anoxic to dysoxic bottom environments. According to PPA and MPS plots of Tyson (1995), the Dabut Formation samples are mostly located within V; IV a, b and IX environments, which represent distal shelf; shelf "dysoxic–suboxic; suboxic–anoxic" and distal to deep marine environments (Figs. 8 and 9). The Mukalla Formation samples are located within distal oxic shelf and distal dysoxic–anoxic shelf environments, as shown from V and VII environments (Figs. 8 and 9). Simple graphic illustrations were used to interpret the percentage data of palynology, phytoclasts, palynomorphs and other components (Figs. 7, 8, and 9) in order to establish paleoenvironmental and paleoecological trends and relationships between the organic geochemical components and the visual study of the studied Mukalla and Dabut samples (Figs. 7, 8, and 9).

In general, three major marine palynofacies (PF 1-3) are recognized in the studied samples of the Mukalla and Dabut Formations (Table 3; Fig. 7). The palynological examination and counting of palynomorph and other palynological component according to procedures of different previous studies on the other parts of the world like Batten (1996a, b); Al-Ameri and Batten (1997); Al-Ameri et al. (1999, 2001).

The palynofacies reflect the multi-cycles of marine transgression and retrogression of deposition of the Mukalla and Dabut Formations. The first palynofacies (PF1) displease an offshore open marine environment as evidenced by increasing of dinoflagellate and foraminiferal test lining components and transgression cycle conditions (Figs. 7, 8, and 9). The second palynofacies (PF2) testify an open marine environment with strong input of river system from northern toward southern parts of the basin within conditions of marine environment as reflected by diversity of miospores, phytoclasts, and microplanktons (Figs. 1, 7, 8, and 9). The third palynofacies (PF3) represents a retregration cycles of nearshore marine environment with input of miospores, phytoclast and other terrestrial materials by river system from north to south (Figs. 1, 7, 8, and 9).

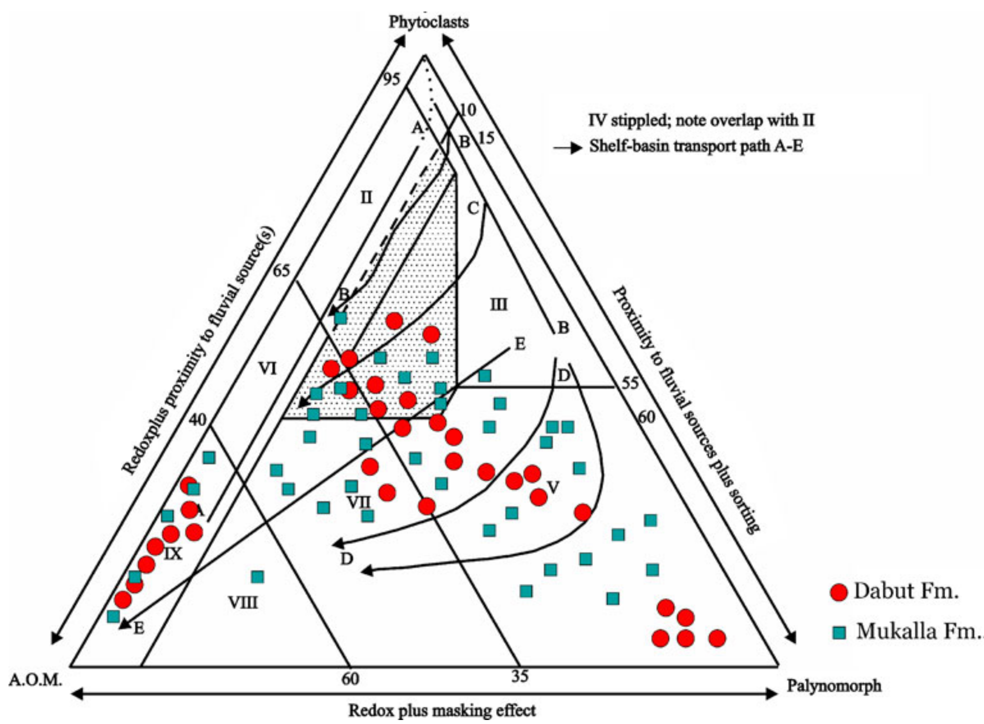

Fig. 8 Ternary amorphous organic matter–phytoclast–palynomorph (APP) kerogen plot based on relative frequency data of 16/G-1 well to characterize the kerogen assemblage and environments (modified after Tyson 1995)

Conclusion

The present analyses of the Late Cretaceous Mukalla and Dabut Formations of the Qamar Basin, eastern Yemen are based on the interpretation of both organic geochemical and organic palynological methods, which are rock-eval pyrolysis/TOC, vitrinite reflectance and palynofacies, to evaluate the organic matter maturity and depositional conditions. The result of TAI, R_0, and T_{max} indicated that the late immature to mature stage of the Mukalla and Dabut Formations. Moreover, the TOC, S_2, PP, and PI results display sufficient organic matter contents to produce oil and gas. The hydrocarbon potentiality is good and capable to make expulsions of oil and gas from the Mukalla and Dabut Formations. Two types of kerogen are found in the Mukalla and Dabut Formations. Two types of kerogen are found in both formation as Type II and Type III. These source rocks are capable of generating petroleum that was discussed and applications of organic geochemistry and optical study indicate that the Mukalla Formation samples are representing the major source rocks of 16/G-1 offshore exploratory well. Mukalla Formation contains more sufficient materials to

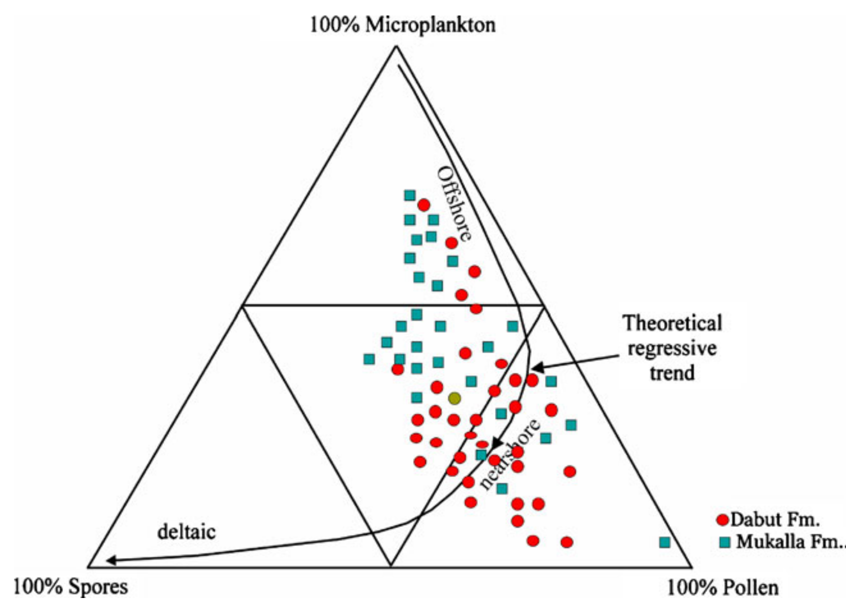

Fig. 9 Ternary microplankton–spore–pollen (MSP) plot to indicate onshore-offshore depositional environments and transgressive-regressive trend of Dabut and Mukalla Formations (Modified after Tyson 1995)

produce oil and gas; kerogen type II and III. Dabut Formation shows less capability to be represented as main source rocks, but may be act as minor source rocks in Qamar Basin. Repetitions of three main marine to shallow marine palynofacies (PF1–PF3) of the Mukalla and Dabut Formations may represent multiple cycles of transgressions to regressions with strong input of river system from north to south direction of Qamar Basin.

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