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Integrating Palynofacies Analysis and Spore Coloration for Assessing Thermal Maturity and Hydrocarbon Potential in Cretaceous Rocks: Safir-N-2 Well, Egypt

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ABSTRACT

Thirty-seven cutting samples from the lower Upper Cretaceous (Albian-Cenomanian age) succession of Safir-N-2 well, north Western Desert of Egypt, were processed palynologically to extract the particulate organic matter (POM). Two palynofacies associations (PFA-1 and PFA-2) were recognized according to quantitative and qualitative changes in the POM constituents. The color alteration of miospores was quantified as Red, Green, and Blue color values (RGB) using Photoshop CC 2022. These values were plotted on a ternary diagram, providing a visual representation of the thermal maturity level. The combined data from the ternary plot and the palynofacies analysis indicates that the Kharita Formation represents a gas phase at a mature stage. In contrast, the lower part of Bahariya Formation represents a gas phase at an immature stage, while its upper part signifies an immature oil phase.

1. Introduction

The presence and distribution of particulate organic matter (POM) within sediment play a role in identifying diverse environments and reconstructing past geographical settings. Palynofacies, a term used to analyze the quantity and quality of POM, initially described the overall microscopic view of organic parts in sediment. Over time, its definition varied among authors, using terms like "organic matter," "palynodebris," or "kerogen" [1].

Since three decades, "kerogen" became the widely accepted term for these organic parts in sedimentary rocks [10]. Palynofacies analysis involves identifying organic components, their proportions, sizes, and states of preservation, to be used as a tool to interpret the possible petroleum sources since it offers direct information on the biological sources and components of POM assemblages [2, 7, 10, 11].

Maturation refers to the thermal decomposition of plants and algal material within sediment, leading to the production of petroleum compounds (i.e., oil, natural gas), and additional byproducts such as CO_2 and water. This process is influenced by both time and temperature [5]. There exist two primary methods to assess the potential of source rock for hydrocarbons: optical techniques, which involve palynofacies analysis, and geochemical analysis, encompassing thermal maturity indices e.g. vitrinite reflectance (Ro), pyrolysis-estimated Tmax temperature (°C). Ibrahim et al. (2002) [3] observed a significant correlation between optical and chemical data when evaluating petroleum potential. Over the past few decades, there has been notable progress in traditional geochemical thermal maturity indices, yet they remain costly and time-intensive. Simultaneously, there is a growing necessity to adapt to the technological advancements in ideas and digital methodologies related to measuring maturation. This underscores the necessity for a contemporary, straightforward, accessible, and efficient index that can complement the classic yet expensive and time-intensive techniques in assessing thermal maturity [8].

Makled and Tahoun (2015) [4] presented a novel approach for assessing thermal maturity through digital measurement of Red, Green, and Blue (RGB) components using professional image processing software like Photoshop™ and Image J. Employing a simple microscopic setup, they tested this method on sporomorphs from various geological eras. Their study revealed that this modified RGB-based technique offers a straightforward and cost-effective way to quickly evaluate thermal maturation, potentially linked to stages of hydrocarbon generation. The objective of this research is to assess the thermal maturity and kerogen types of samples retrieved from the Kharita and Bahariya formations within the Safir-N-2 well in Egypt's Matruh Basin. This involves two main steps: initially, recognizing various palynofacies types through visual analysis to determine kerogen quality, and secondly, employing the RGB-based method to detect spore color alterations. These approaches aid in detecting maturity levels and appraising the hydrocarbon potential of these specific source rocks.

2. Materials and Methods

Thirty-seven cutting samples were selected to encompass the lower Upper Cretaceous (Albian-Cenomanian age) Kharita and Bahariya formations, ranging from 2301 to 1762 m within the Safir-N-2 well in the north Western Desert of Egypt (Fig. 1). The samples were prepared by the conventional palynological preparation procedure of Traverse (2007) [9]. This paper's methodology comprised two primary steps. Initially, the analysis aimed to identify different palynofacies types visually, assessing kerogen quality. Subsequently, an RGB-based method was employed to detect alterations in spore coloration, aiding in evaluating maturity levels and appraising hydrocarbon potential in specific source rocks. To assess kerogen quality, the first 500 grains of total POM on each slide were counted according to Tyson (1993) [10]. The *Deltoidospora* spp. (three-ten grains from each slide based on the richness of the sample) were selected as representative psilate spores, and were photographed to aid in the assessment of thermal maturity by detecting color alterations in these specific spores. These were chosen due to their long stratigraphic range and the notably thin exine structure. The colors of these specimens were quantified using the Photoshop CC 2022 program.

Certain precautions were taken into consideration to such digital RGB measurements; e.g., exceptionally lighter (caved) or darker (reworked) specimens were excluded from the RGB coloration population samples to avoid any potential misleading results, and mean values for Red (R), Green (G), and Blue (B) were taken to minimize errors. The RGB color readings were plotted on a ternary diagram, a free online program available at https://www.ternaryplot.com/, featuring includes three distinct fields that correspond to the immature, mature, and post mature domains. These readings were then calibrated with the RGB color readings plot of Pearson's 1984 scale[6], as outlined by Makled and Tahoun (2015) [4], to calculate the numerical thermal alteration index (TAI) (Fig. 2). This index was further correlated with the Pearson's 1984 colored scale (Fig. 3) to estimate the theoretical Ro, representing the level of thermal maturity.

3. Results and Discussion

3.1. Palynofacies and Kerogen

The palynofacies are divided into three groups based on Tyson's classification system (1993): palynomorphs, phytoclasts, and amorphous organic matter (AOM).

Palynomorphs encompass various elements like spores, pollen, dinoflagellates, foraminiferal inner test linings, certain types of microscopic algae, acritarchs, and chitinous fungal spores. Phytoclasts refer to tissue fragments from higher plants, fungi, or algae, which can appear either opaque or translucent depending on their oxidation state. AOM comprises all structureless components of kerogen, originating from marine or non-marine sources. The sediments of the Safir-N-2 well exhibit two distinct palynofacies associations, delineated by the variation in the composition of POM as follows:

3.1.1. Palynofacies association-1 (PFA-1) (phytoclast and opaque major domination)

Between the depths of 2301–1999 m within the Kharita and Bahariya formations, this facies is notably marked by a significant abundance of phytoclasts (ranging from 62% to 78% with an average of 71%), in addition to a moderately abundant AOM ranging from 20% to 35% and averaging at 28%, while palynomorphs are very rare (5%) (Fig. **4**). The phytoclasts primarily comprise opaque and non-opaque fragments from terrestrial plants, such as tracheids, cuticles, and lignified xylem (Fig. **4**). Opaque phytoclasts make up 37% to 65% (averaging 51%) and are characterized by well-preserved lath- (ranging from 40% to 64%, averaging 53%) in addition to equant-shaped fragments (1% to 4%) displaying various sizes and colors from dark brown to black.

Translucent phytoclasts, constituting 12% to 39% (averaging 20%), consist of biostructure (3% to 10%, averaging 6%) and non-biostructure elements (1% to 21%, averaging 10%), occasionally including rare cuticle (Fig. **6**). The AOM can originate from natural products such as resin (1%) or result from the biodegradation of land plant tissues and/or phytoplankton, ranging from 20% to 35% (averaging 27%). The resin typically appears as round, homogenous, hyaline products (glassy shards), while the decomposed plant tissue and/or phytoplankton presents diffuse-edged structures varying from transparent, pale yellow to yellow, and orange (Fig. **6**). The presence of significant quantities of phytoclasts (wood and plant debris) indicates that the recommended kerogen type for this facies is Type III, which is prone to gas formation.

3.1.2. Palynofacies association-2 (PFA-2) (AOM major domination)

The facies located between 1972–1762 m within the Bahariya Formation is denoted as PFA-2.

It is characterized by a notable increase in the amounts of AOM (averaging 49%, varying from 40% to 60%), with a portion (2%) of this comprising resin. Simultaneously, there's a decline in phytoclast amounts (averaging 51%, ranging from 39% to 59%). Palynomorphs, in contrast, are notably scarce, accounting for only 2% (Fig. **5**). The AOM is comprised of well-preserved particles displaying various colors such as yellow, orange, brown, and dark brown. While most recorded fragments exhibit diffused edges, granular varieties are also present in smaller quantities. Phytoclasts in PFA-2 share similarities in form and color with those described in PFA-1. Notably, the phytoclast group decreases, whereas opaques constitute a higher proportion (average 41%, ranging from 27% to 59%), along with translucent phytoclasts (average 11%, ranging from 6% to 12%) (Fig. **6**). This facies is indicative of Kerogen Type II, characterized as oil-prone material, primarily due to the substantial presence of AOM and frequent occurrences of phytoclasts.

3.2. Organic thermal maturity

The examined succession in the Safir-N-2 well consistently exhibits a marked increase in color intensity as depth increases. TAI values vary within the range of 1+, 2-, 2, 2+, 3- to 3, corresponding to a thermal maturity range of 0.3 to 0.98% Ro (Fig. **7**). When assessing maturity levels, both the Kharita and Bahariya formations in the Safir-N-2 well can be characterized as follows:

3.2.1. Kharita Formation (Depths from 2301 to 2036 m)

The dominance of mature palynomorphs, exhibiting colors ranging from orange to light brown and medium brown, signifies a notable elevation in TAI values from 2+, 3- to 3. This color intensity progression corresponds to Ro values in the range of 0.61 to 0.98%, as depicted in Fig. **7**.

3.2.2. Bahariya Formation (Depths from 2027 to 1762 m)

It is characterized by the prevalence of predominantly immature palynomorphs displaying a color spectrum ranging from pale to medium yellow. This aligns with a TAI of 1+, 2-, 2 and a corresponding Ro value ranging from 0.3 to 0.45%, as illustrated in Fig **7**.

3.3. Hydrocarbon potentiality

The Safir-N-2 well reveals three potential horizons for both mature and immature source rocks, recognized through the ternary plot of thermal maturity (Fig. **2**) as follows:

3.3.1. Mature gas-prone source rocks

The identified mature source rock horizon in the Safir-N-2 well is proposed to lie within the Kharita Formation, from 2301 to 2036 m. This conclusion is drawn from the significant prevalence of phytoclasts (62%-78%) and the minor dominance of AOM (20%-35%) (Fig. 6). Additionally, the presence of thermally mature palynomorphs exhibiting colors ranging from orange to light-medium brown supports this assessment, TAI values of 2+, 3- to 3, and Ro values within the range of 0.61 to 0.98%, as indicated in Fig. 7. This horizon is suggested to be conducive to gas generation.

3.3.2. Immature gas-prone source rocks

These are suggested to be in the Bahariya Formation at intervals 2027–1999 m. This result is based on major domination of phytoclasts (68%-78%) and minor domination of AOM (21%-29%) (Fig. 6), in addition to thermally immature palynomorphs of pale to medium yellow color reflecting 2 TAI and 0.45% Ro (Fig. 7). A biogenic gas is proposed for this horizon.

3.3.3 Immature oil-prone source rocks

The inferred immature source rock horizon in the Safir-N-2 well is proposed to be within the Bahariya Formation, occurring within the intervals of 2027–1999 m. This conclusion is drawn from the substantial prevalence of phytoclasts (68%-78%) and the minor dominance of AOM (21%-29%) (Fig. 6). Furthermore, the presence of thermally immature palynomorphs exhibiting colors ranging from pale to medium yellow supports this interpretation, reflecting TAI of 1+, 2- and Ro values within the range of 0.3 to 0.38%, as illustrated in Fig. 7. This horizon is suggested to contain biogenic oil but in immature stage.

4. Conclusion

The palynofacies analysis of 37 cutting samples from the Kharita and Bahariya formations in the Safir-N-2 well identified two distinct Palynofacies Associations (PFAs): PFA-1, characterized as gas-prone, and PFA-2, characterized as oil-prone. This comprehensive examination coupled with the quantification of spore colors offer valuable insights into the maturity stages and hydrocarbon potential of the studied formations, demonstrating a gas phase at a mature stage in the Kharita Formation and an oil phase at an immature stage in the upper part of the Bahariya Formation, contrasting with the lower part representing a gas phase at an immature stage.

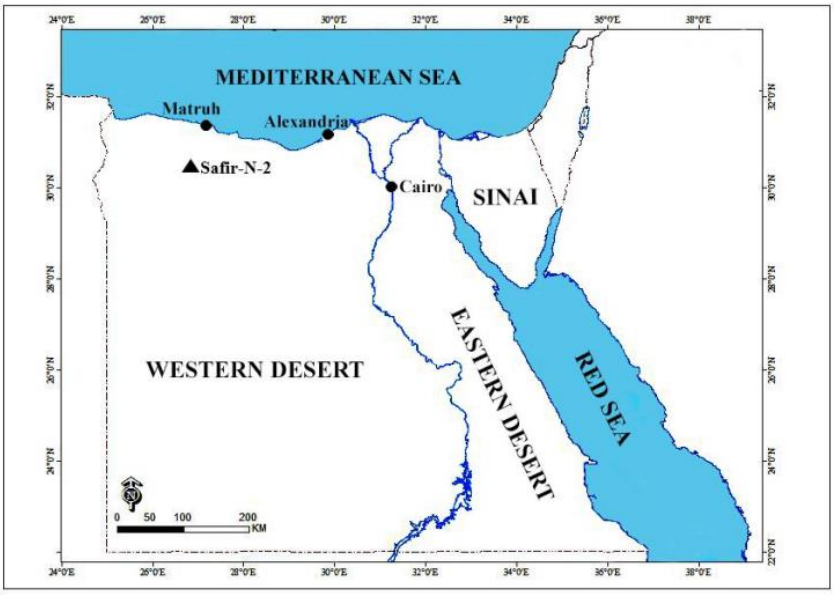


Fig. 1. Location map of the studied Safir-N-2 well in north Western Desert, Egypt.

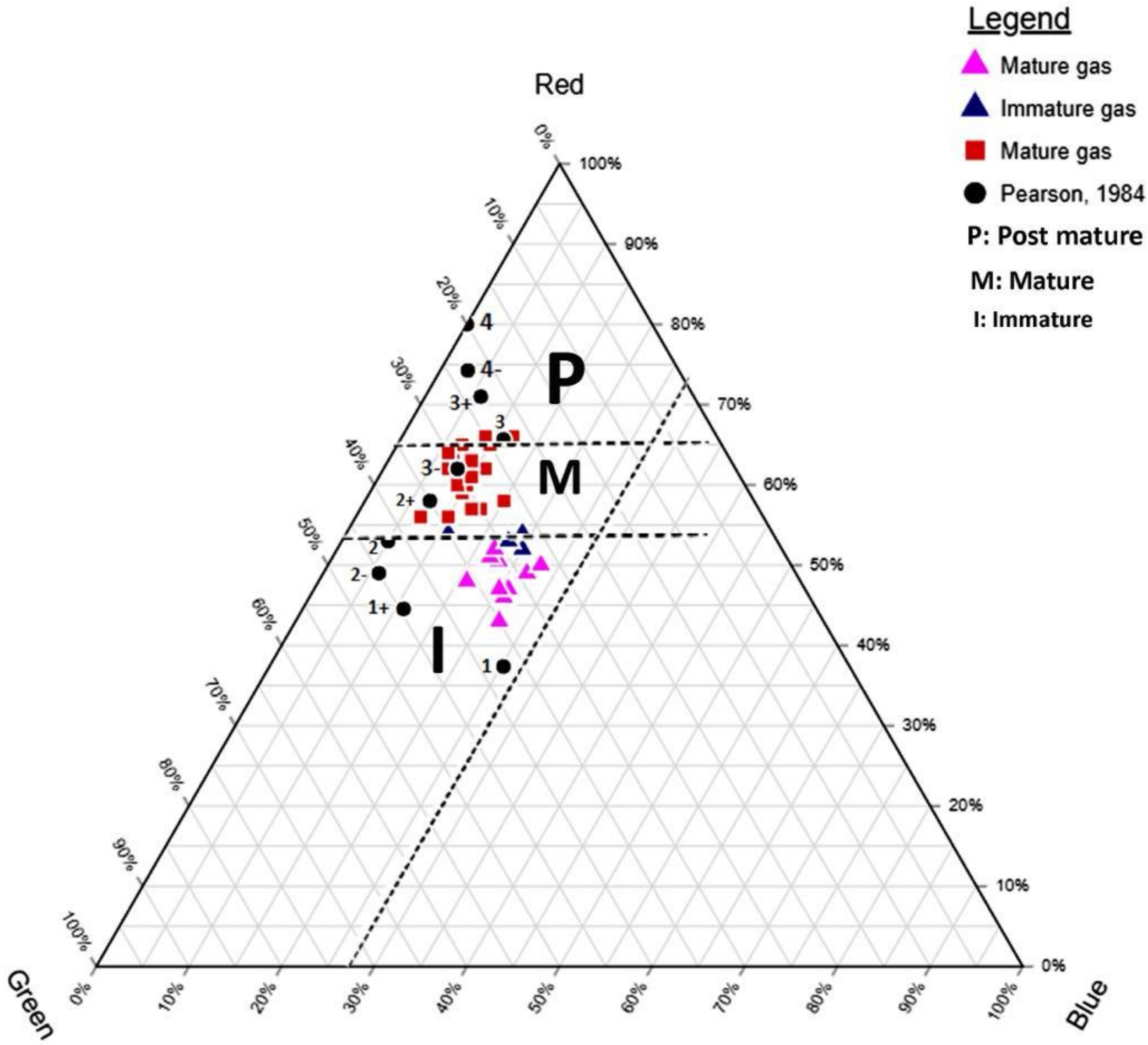


Fig. 2. A ternary plot illustrating RGB color readings of Pearson's 1984 and *Deltoidospora* spp. from the Albian-Cenomanian of Safir-N-2 well.

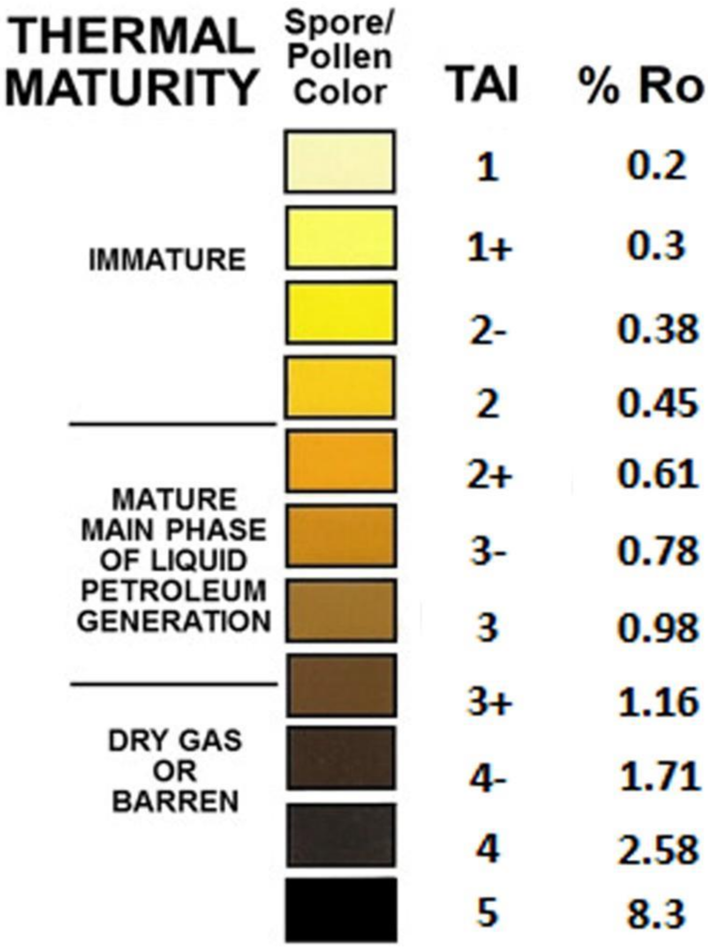


Fig. 3. Pearson's colored scale (1984) compared with thermal alteration index (TAI) and vitrinite reflectance (Ro).

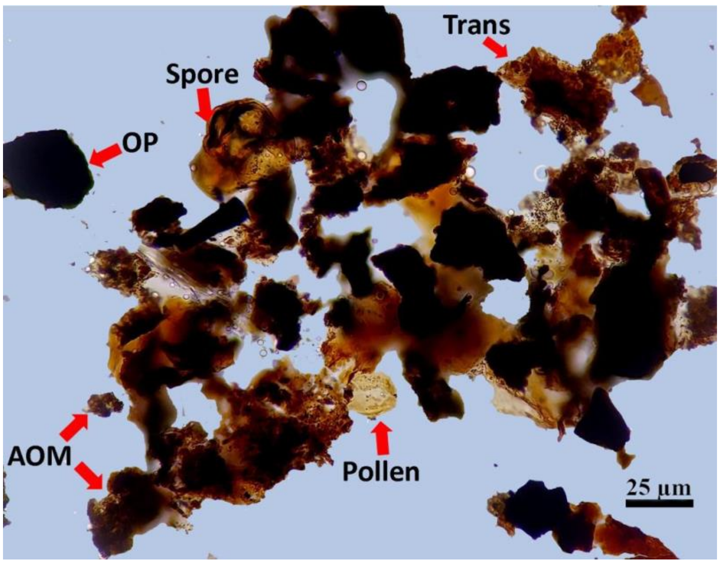


Fig. 4. An abundant phytoclast facies representing palynofacies zone 1 (PFA-1); AOM= amorphous organic matter, Op=opaque, Trans=translucent.

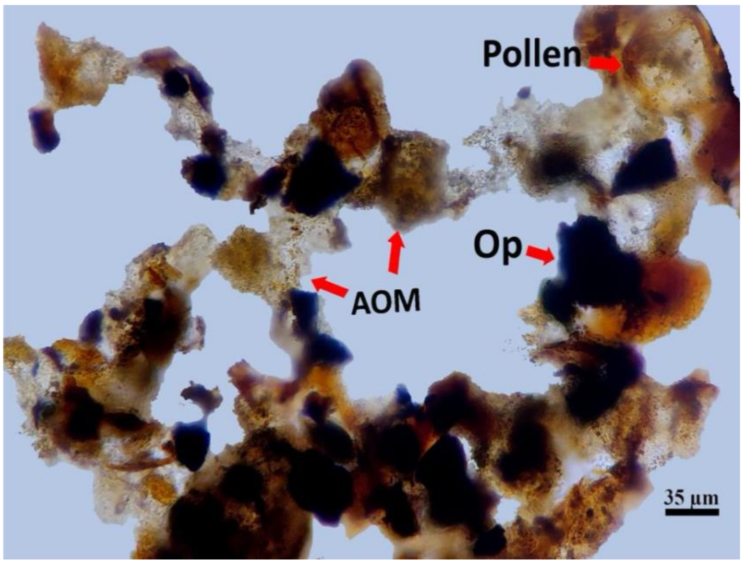


Fig. 5. An abundant amorphous facies representing palynofacies zone 2 (PFA-2); AOM= amorphous organic matter, Op=opaque.

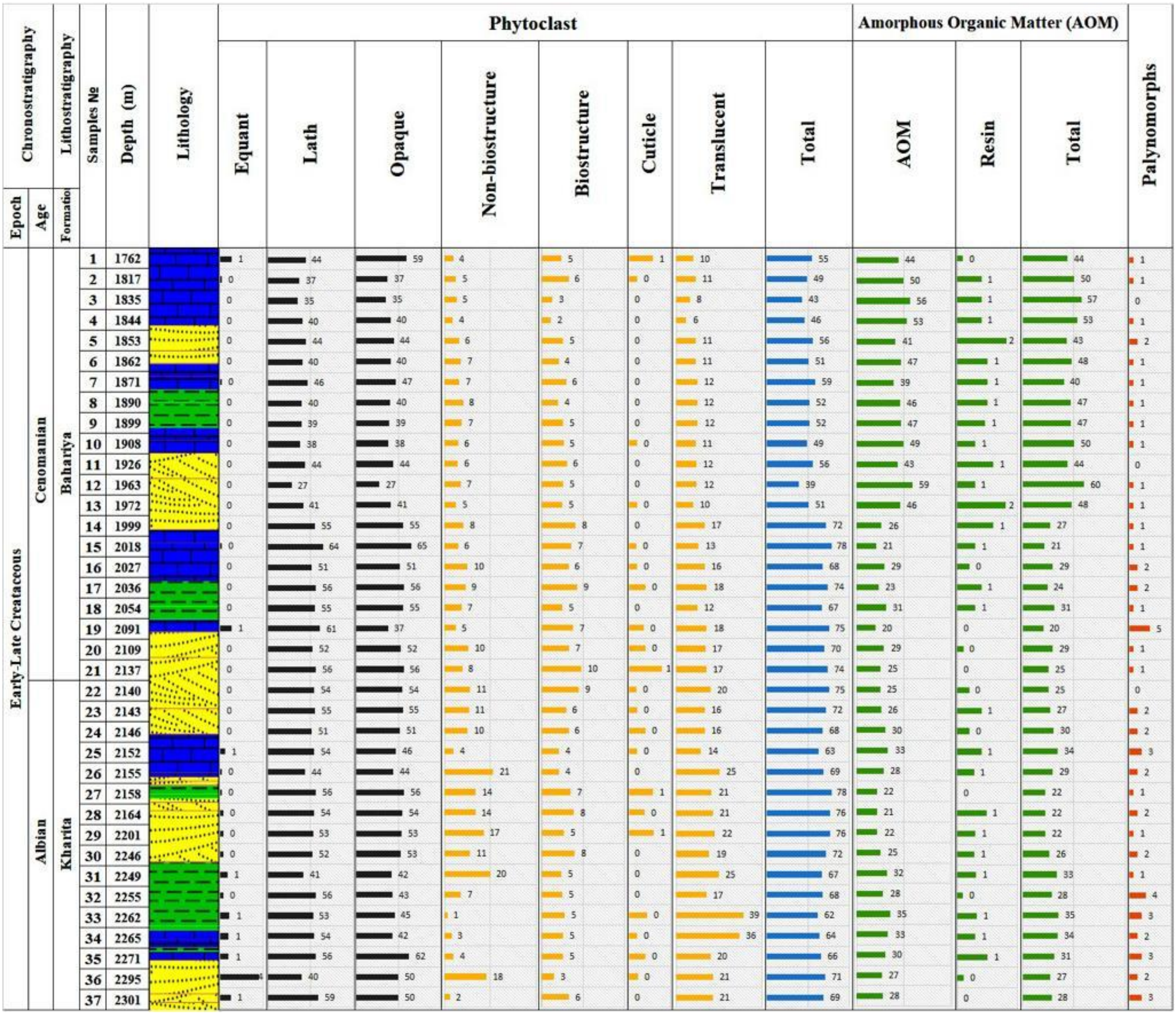
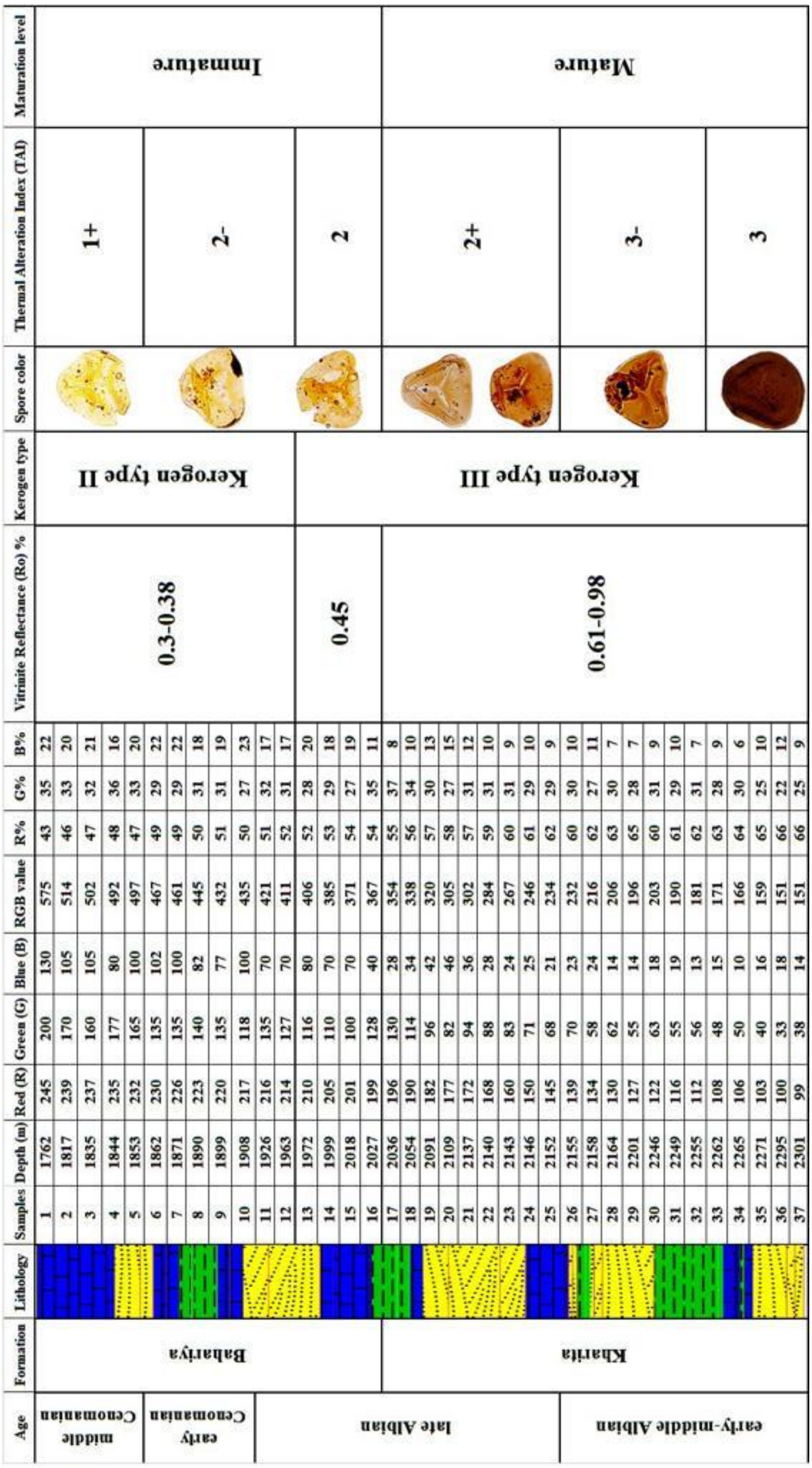


Fig. 6. A chart depicting the semi-quantitative palynofacies analysis of the studied samples from Safir-N-2 well.



Age	Formation	Samples	Depth (m)	Red (R)	Green (G)	Blue (B)	RGB value	R%	G%	B%	Vitrinite Reflectance (Ro) %	Kerogen type	Thermal Alteration Index (TAI)	Maturation level
middle Cenomanian	Bahariya	1	1762	245	200	130	575	43	35	22	0.3-0.38	Kerogen type II	1+	Immature
		2	1817	239	170	105	514	46	33	20				
		3	1835	237	160	105	502	47	32	21				
		4	1844	235	177	80	492	48	36	16				
		5	1853	232	165	100	497	47	33	20				
early Cenomanian		6	1862	230	135	102	467	49	29	22			2-	
		7	1871	226	135	100	461	49	29	22				
		8	1890	223	140	82	445	50	31	18				
		9	1899	220	135	77	432	51	31	19				
		10	1908	217	118	100	435	50	27	23				
late Albian		11	1926	216	135	70	421	51	32	17				
		12	1963	214	127	70	411	52	31	17				
		13	1972	210	116	80	406	52	28	20	0.45	Kerogen type III	2	
		14	1999	205	110	70	385	53	29	18				
		15	2018	201	100	70	371	54	27	19				
		16	2027	199	128	40	367	54	35	11				
	Kharita	17	2036	196	130	28	354	55	37	8	0.61-0.98		2+	Mature
		18	2054	190	114	34	338	56	34	10				
		19	2091	182	96	42	320	57	30	13				
		20	2109	177	82	46	305	58	27	15				
		21	2137	172	94	36	302	57	31	12				
		22	2140	168	88	28	284	59	31	10				
		23	2143	160	83	24	267	60	31	9				
		24	2146	150	71	25	246	61	29	10				
		25	2152	145	68	21	234	62	29	9				
early-middle Albian		26	2155	139	70	23	232	60	30	10			3-	
		27	2158	134	58	24	216	62	27	11				
		28	2164	130	62	14	206	63	30	7				
		29	2201	127	55	14	196	65	28	7				
		30	2246	122	63	18	203	60	31	9				
		31	2249	116	55	19	190	61	29	10				
		32	2255	112	56	13	181	62	31	7				
		33	2262	108	48	15	171	63	28	9			3	
		34	2265	106	50	10	166	64	30	6				
		35	2271	103	40	16	159	65	25	10				
		36	2295	100	33	18	151	66	22	12				
		37	2301	99	38	14	151	66	25	9				

Fig. 7. The theoretical vitrinite reflectance (Ro), thermal alteration index (TAI), maturity levels, RGB parameters data, and kerogen types of the studied samples.

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