Palaeobiodiversity and Palaeoenvironments (2021) 101:35–50
https://doi.org/10.1007/s12549-020-00474-9

SENCKENBERG

ORIGINAL PAPER

Palynofacies as a palaeoenvironment and hydrocarbon source potential assessment tool: An example from the Cretaceous of north Western Desert, Egypt

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Received: 19 March 2020 / Revised: 9 November 2020 / Accepted: 9 December 2020 / Published online: 8 March 2021

Abstract

Optical examination employing transmitted light and UV-fluorescence microscopy of palynological preparations of eighteen cutting samples representing the Alam El Bueib Member (Hautervian-Barremian), Kharita/lower Bahariya (Cenomanian), and Abu Roash (Turonian-Santonian) formations collected from the Faghur Hj5-1 well, north Western Desert, Egypt, allows the identification of three different palynological assemblages from the studied rock units. These assemblages are mainly non-marine but apparently marine at the base of the Alam El Bueib Member, as evidenced by dinocyst occurrence. In addition, the presence of the *Pediastrum* and chlorophycean algae ecozone, recognised in previous works, is a good datum for the Abu Roash Formation in the north Western Desert of Egypt. Three associations of palynofacies linked to lithofacies changes are recognised and employed in identification of depositional environments. The Alam El Bueib samples yielded mixed kerogen assemblages of non-marine and marine organic facies. The Kharita/lower Bahariya interval is mostly barren, possibly due to prevailing sandstone lithofacies, except for one sample at its upper part which contains a diverse palynological assemblage. The overlying Abu Roash Formation has a homogeneous kerogen composition comprising mainly granular fluorescent AOM and algae as well as rare palynomorphs. Qualitative as well as quantitative variations of palynofacies allow the reconstruction of the depositional environment. The obtained data have the potential for discriminating spatial and redox status differences and providing also information about terrestrial/freshwater influxes. Results support the model that the Alam El Bueib Member was deposited in a marginal dysoxic-anoxic to distal suboxic-anoxic basin. The Kharita/lower Bahariya unit in the studied well was deposited under marginal dysoxic-anoxic conditions whereas the overlying Abu Roash Formation in a distal suboxic-anoxic basin. Palynofacies results also show that the studied material comprises two distinct facies of kerogen. First, Type II > I kerogen (AOM-rich) is overwhelmingly dominant in the Abu Roash Formation and a few samples from the Alam El Bueib Member which are presumed highly oil-prone, whereas Type III kerogen (phytoclast-rich) is particularly common in the Alam El Bueib Member and Kharita/lower Bahariya unit which are considered gas-prone. Thermal maturity determinations obtained from colour changes of smooth-walled palynomorphs reveal that Alam El Bueib samples belong to immature to mature stages; however, Kharita/lower Bahariya and Abu Roash samples are within the immature phase.

Keywords Palynology · Palynofacies · Cretaceous · North Western Desert · Egypt

Introduction

The northern part of the Western Desert, Egypt, is an important province in terms of petroleum plays that has witnessed continuous exploration activity for hydrocarbons since 1940 until now, as demonstrated by the recent discovery in the studied Faghur Basin (OGJ 2018). Moreover, the Cretaceous system is one of the most important targets in the exploration for petroleum in this region. As a result, palynological investigations of subsurface Cretaceous deposits have been carried out extensively and demonstrated the presence of abundant

This article is a contribution to the special issue "Palaeobotanical contributions in honour of Volker Mosbrugger"

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palynomorphs, especially those dealing with Upper Cretaceous successions (e.g. El Beialy et al. 2010 and citations therein). However, little is known about the specific changes related to palynofacies and kerogen quality. Acquiring this information is important especially when there is a need to understand the relationship between depositional environment and petroleum potential within such an economically important area.

The present article is based on palynological investigation of eighteen subsurface samples representing the Alam El Bueib, Kharita/lower Bahariya, and Abu Roash rock units collected from the Faghur Hj5-1 well, latitude 29° 54′ 20.03′′ N and longitude 25° 28′ 02.03″ E (Fig. 1).

The current study attempts to (1) focus on the palynomorph distribution, (2) introduce an age assignment of the studied succession of the Faghur Hj5-1 well, (3) correlate the palynomorph assemblages with their local and regional counterparts, (4) provide insights into climate and floral provincialism of the recorded taxa, and (5) identify palynofacies types and provide insights into kerogen quality and thermal maturity, which is valuable in the analysis of depositional environment and petroleum potential determination.

Geologic setting

The Western Desert of Egypt covers an area of approximately 700,000 km^2, which represents about two thirds of the total area of the country. Structurally, the northern Western Desert which belongs to the unstable shelf (Said 1962), was tectonically active during most of the Palaeozoic to the early Cenozoic, when basin reconfigurations occurred (Hantar 1990).

According to Dolson et al. (2000), by the Early Cretaceous, a prolonged period of thermal subsidence associated with the development of a wide passive margin occurred across the northern margin of the African plate, resulting in a mixed siliciclastic and carbonate system. The Alam El Bueib Member contains marine carbonate source rocks and is overlain by carbonate micrite and oolitic limestone cycles that

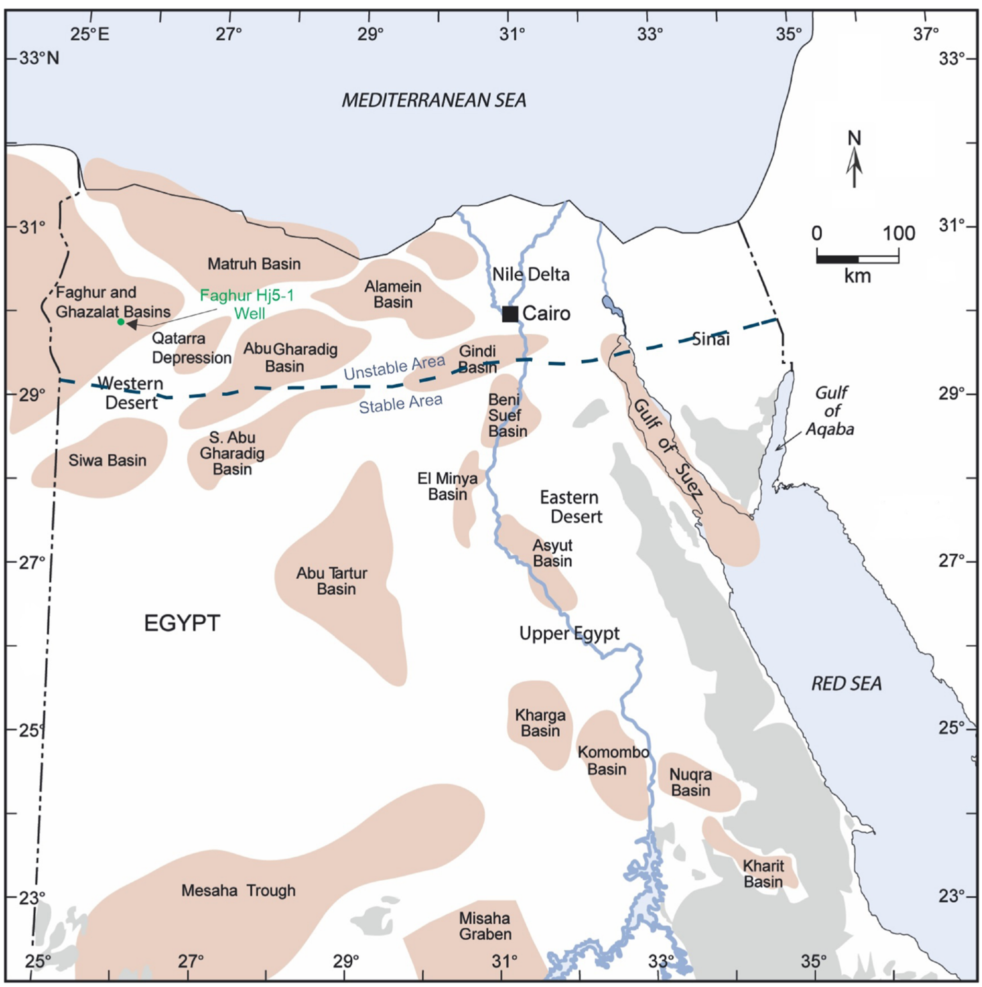


Fig. 1 Location map showing the sedimentary basins of Egypt and the studied Faghur Hj5-1 well, based on Dolson et al. (2000)

indicates a series of transgressions and regressions linked to regional sea-level oscillations. Persistent thermal subsidence throughout the Western Desert was accompanied by southward transgressions across the stable carbonate shelf and resulted in the widespread deposition of source rocks in the Kharita and Bahariya formations.

Lithostratigraphic framework

The sedimentary succession of the north Western Desert consists of strata spanning in age from Cambrian-Ordovician to Quaternary, attaining a thickness of more than 10,600 m at the graben of the Abu El Gharadig Basin (Schlumberger 1995). The studied interval in the Faghur Hj5-1 borehole is subdivided from base to top into the Cretaceous Alam El Bueib, Kharita/lower Bahariya, and Abu Roash rock units (Fig. 2).

Alam El Bueib Member

The Alam El Bueib Member (a subdivision of the Burg El Arab Formation) is composed of a sandstone unit with frequent shale interbeds in its lower part and occasional limestone beds in its upper part. Its type succession is in the Alam El Bueib-1 well (Hantar 1990). In the studied borehole, the Alam El Bueib Formation occurs from 3875 to 4120 ft., a 245-ft. (74.7 m) total thickness. It overlies the Alamein Dolomite and underlies unconformably the Kharita Formation from the Kharita/lower Bahariya interval.

Kharita/lower Bahariya interval

The Kharita Formation is composed of fine- to coarse-grained sandstone with subordinate shale and carbonate interbeds; its type succession is in the Kharita-1 well (Hantar 1990). The Bahariya Formation was defined by Said (1962) and El Akkad and Issawi (1963) and measured 170-m thick in its type section at Gebel El Dist, north of the Bahariya Oasis. In subsurface successions, it has been divided into six units, of which unit I (upper pay) and unit IV (lower pay) are potential hydrocarbon-bearing zones (Schlumberger 1984). In the studied succession, the Kharita/lower Bahariya interval occupies 2788 to 3875 ft.; 1087-ft. (331 m) thick within the studied well.

Abu Roash Formation

The Abu Roash Formation was first described by Beadnell (1902) and termed as "Formation" by Norton (1967). It is mainly a limestone sequence with interbeds of shale and sandstone; its type locality is the classic Abu Roash structure to the north of the Giza Pyramids (Hantar 1990). The Abu Roash Formation was subdivided into a number of informal subsurface members designated as A–G Members (Norton 1967; Schlumberger 1984). The studied interval in the Faghur Hj5-1 well ranges in thickness from 2345 ft. to 2788 ft., 443-ft. (135 m) thick, and is overlain by the Khoman Formation and unconformably underlain by the Bahariya Formation.

Material and methods

Eighteen cutting samples from the Alam El Bueib, Kharita/lower Bahariya, and Abu Roash formations (Fig. 2) are palynologically examined for this study. Around 15–20 g of each sample was prepared for palynological analysis following standard extraction techniques including HCl-HF demineralization treatment (e.g. Wood et al. 1996). Afterwards, the residues were sieved using 10-μm nylon meshes; soft soap was added to some residues to assist in sieving. No oxidative acids were employed. An aliquot of the kerogen concentrate residue of each sample was mounted on coverslips dried at 30–40 °C to get a single plane of focus and adhered to the coverslip using Lucite International's Elvacite 2044 acrylic resin dissolved in xylene. All slides and residues are deposited at the Department of Geology, Faculty of Science, Mansoura University, Egypt.

Semi-quantitative and qualitative analyses have been done. Counts of 300 organic particles per sample are made (a minimum count of 100 particles was registered for a few samples) through several traverses (Table 1). This counting technique provides an adequate estimate of the organic matter types in the samples. Microscopic investigation and photomicrographs were made using JVC KY-F75U and Nikon DS-1QM/H cameras attached to a Nikon Eclipse 90i microscope. Following the counting, the kerogen slides were examined under both transmitted and fluorescence microscopy to provide a qualitative assessment of the character of the organic components.

The classification of organic particles follows that summarized by Batten (1996), which categorized palynological matter into three main subdivisions: (1) palynomorphs, (2) structured organic matter (both phytoclasts and zooclasts), and (3) unstructured (structureless) organic matter which encompasses amorphous organic matter (AOM), gelified matter, resin, and amber and solid bitumen. For the purpose of this study three main divisions of palynomorphs, phytoclasts and AOM were recognised. The variation in the bulk composition among these categories (Fig. 2) is traced in an effort to elucidate palaeoenvironmental conditions of the studied intervals. This simply follows the fact that environments are characterised by definite palynofacies assemblages, denoting a link between environment of deposition and source rock potential. The quantitative data are plotted in the ternary diagram after Tyson (1989) to help in the environmental interpretation.

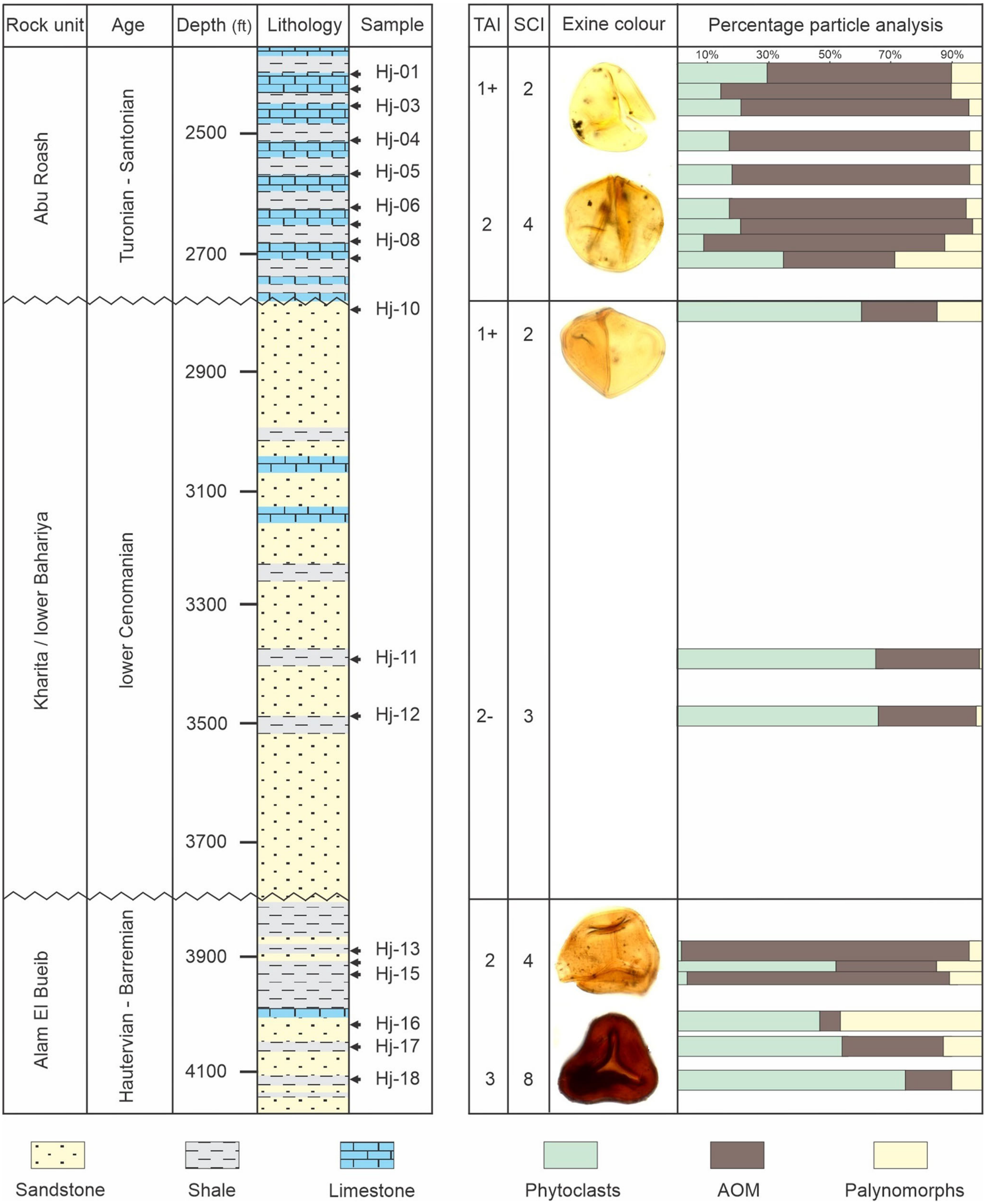


Fig. 2 Lithostratigraphic log of the studied rock units in the Faghur Hj5-1 well (based on Khalda 1990), as well as the distribution of main kerogen parameters

Table 1 Quantitative distribution of palynofacies data from the studied well

Sample	Depth (ft)	Rock unit	Phytoclasts	AOM	Palynomorphs		APP count	Microforaminiferal test linings	Algae			Total count
					Sporomorphs	Dinocysts			*Pediastrum*	*Scenedesmus*	*Botryococcus*	
Hj-01	2400	Abu Roash	90	180	12	18	300	3	47	0	17	367
Hj-02	2430		44	225	13	18	300	14	106	0	2	422
Hj-03	2460		60	210	2	10	282	4	175	0	5	466
Hj-04	2520		51	234	5	7	297	1	110	0	1	409
Hj-05	2580		56	225	13	6	300	2	1	0	3	306
Hj-06	2640		36	160	8	3	207	2	150	5	0	364
Hj-07	2670		63	228	2	7	300	2	150	10	0	462
Hj-08	2700		21	170	4	23	218	4	90	5	0	317
Hj-09	2730		105	110	74	11	300	3	40	0	0	343
Hj-10	2790	Kharita/ lower Bahariya	182	74	34	10	300	9	50	5	0	364
Hj-11	3380		65	34	1	0	100	0	0	0	0	100
Hj-12	3480		66	32	2	0	100	0	0	0	0	100
Hj-13	3890	Alam El Bueib	2	94	2	2	100	0	2	0	0	102
Hj-14	3910		155	100	45	0	300	0	0	0	0	300
Hj-15	3930		3	77	10	0	100	2	4	0	0	106
Hj-16	4020		140	20	137	3	300	2	0	0	0	302
Hj-17	4060		112	69	15	12	208	0	1	1	0	210
Hj-18	4120		224	45	27	4	300	0	1	0	0	301

Results

Palynological and palynofacies contents of each unit are described and the interpretation of their environment of deposition and petroleum potential is also provided.

Alam El Bueib association

The kerogen assemblages recorded from the studied Alam El Bueib Member are moderately preserved and diverse. Phytoclasts are the dominant palynofacies component (47–75%) with variable percentages of AOM (7–33%) and palynomorphs (10–15%), except for sample Hj-16 which reached up to 47% palynomorphs and the samples Hj-13 and Hj-15 that display higher AOM concentrations (up to 94%) and lesser phytoclast content (Fig. 2). Phytoclasts are dominated by opaques that are generally lath-shaped, sometimes equidimensional, probably derived from stems and root tissues (sometimes referred to charcoal). Other phytoclast elements are cuticles and wood including tracheids as well as other biodegraded plant tissues. AOM is generally of medium grey to yellowish or brownish grey colour, non-fluorescent with a uniformly granular appearance, and hosts framboidal pyrite inclusions that may represent sulphur reducing bacterial activities (Batten 1983). AOM with pyrite inclusions is regarded as an indication that it has been accumulated under dysoxic to anoxic conditions (Tyson 1995). The recorded non-fluorescent AOM points to humic rather than exinitic or lipid-containing organic matter (Tyson 1984), and hence resembles terrestrial AOM or altered phytoclasts, comparable with AOM type B of Thompson and Dembicki (1986) with a minor contribution of type C.

Non-marine assemblages composed of terrestrial palynomorphs mainly circumpoll pollen grains, such as *Classopollis* and *Circulina*, rarely as tetrads (Figs. 3g, h, 4h) are retrieved from the Alam El Bueib Member. Associated palynomorphs tend to be mostly gymnosperm pollen, particularly *Araucariacites*, *Balmeiopsis*, *Callialasporites*, *Inaperturopollenites* and infrequent *Ephedripites*. Moreover, pteridophyte spores are moderately diverse, but overall, they are numerically fewer than gymnosperms (Appendix 1). Angiosperms are also very rare and represented exclusively by *Afropollis* (Fig. 4i), *Tucanopollis crisopolensis*, and *Stellatopollis* (Fig. 4e). Rare occurrences of marine dinocysts as well as microforaminiferal test linings were noted. The occurrence of dinocyst taxa *Circulodinium, Coronifera*, *Oligosphaeridium*, *Spiniferites*, and *Subtilisphaera* together with microforaminiferal test linings suggests deposition in a coastal or shallow marine environment of normal salinity (Mahmoud et al. 2007). In addition, few chlorophycean algae such as *Pediastrum* and *Scenedesmus* were recorded. The persistence of strong terrestrial influence generally supports deposition within a near-shore environment. Similar palynological results have been recently obtained from the Alam El Bueib Member of the OBA. 3-1/1A and OBA. S-C wells (El Atfy et al. 2019a, b), north Western Desert, Egypt.

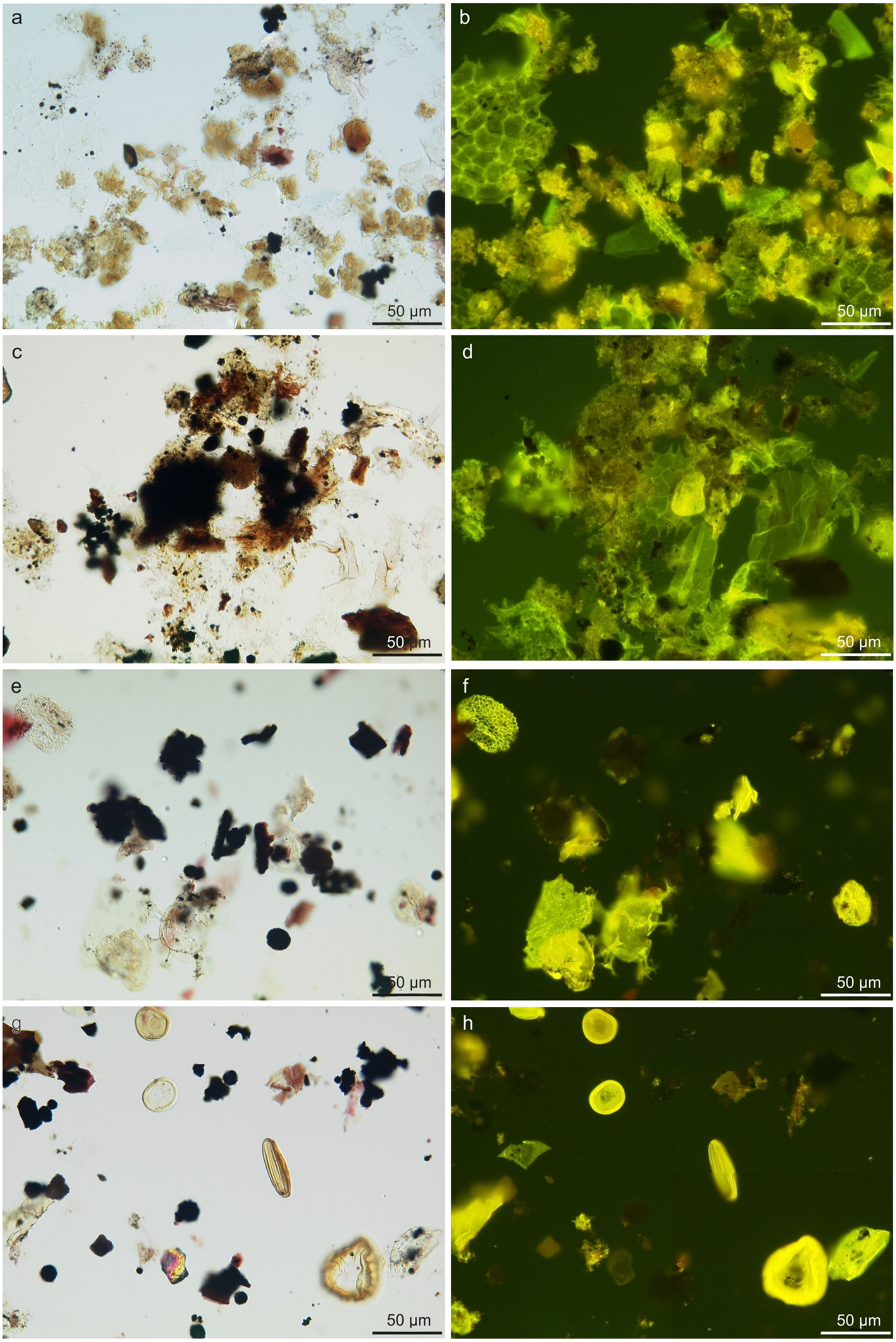
Plotting data in the AOM-phytoclast-palynomorph (APP) ternary kerogen diagram of Tyson (1989) reveals that Alam El Bueib samples are located mainly within fields II, IX, and only one sample in field III (Fig. 5). Field II implies kerogen Type III (gas-prone) and deposited under marginal dysoxic-anoxic conditions, whereas field IX refers to kerogen Type II > I (highly oil-prone) and deposited under distal suboxic-anoxic conditions.

Fig. 3 **a**, **b** Mixed palynofacies assemblage composed mainly of fine granular, yellow to grey marine AOM, presumably of algal origin (highly fluorescent) invaded with some pyrite crystals together with *Pediastrum* coenobia and phytoclasts, Hj-01_EF J31-1. **c**, **d** Mixed palynofacies assemblage comprises mainly fluorescent AOM, phytoclasts, and *Pediastrum* coenobia, Hj-05_EF R34-0. **e**, **f** Mixed palynofacies assemblage composed mainly of opaques with disseminated pyrites, pollen and dinocysts, Hj-16_ EF N35-3. **g**, **h** *Classopollis*-rich palynofacies in association with *Ephedripites* and opaques, Hj-16_ EF N43-2

Kharita/lower Bahariya association

The overlying sequence in the depositional history of the studied well is the Kharita/lower Bahariya succession, which is represented by three samples: Hj-10, Hj-11, and Hj-12. The two latter samples seem to be barren and contain poor organic residues, possibly attributable to their sandy facies (Fig. 2). The palyniferous interval within this sequence yielded phytoclasts (mainly opaque) which represent the most common organic contributor (> 60%); they include cuticle and wood particles that are mostly well preserved. Fluorescent granular AOM (25–34%), in colour yellow to yellowish-brown, includes a considerable percentage of resin shards. Masran and Pocock (1981) suggested that resin is derived from terrestrial material and mostly produced by angiosperm trees in tropical climates (Tyson 1995). The palynomorph composition (1–4%) is represented by abundant terrestrial assemblages. Pollen and spore assemblages are composed of diverse pteridophytic spore and pollen taxa such as *Classopollis brasiliensis*, *Integritetradites porosus*, *Afropollis jardinus*, *Afropollis kahramanensis*, and *Ephedripites* spp. (Appendix 1). Microplankton is represented mainly by frequent *Pediastrum* and *Scenedesmus*, marine dinocysts (e.g. *Odontochitina* and *Subtilisphaera*), as well as rare/common microforaminiferal test linings.

APP ternary kerogen plot (Fig. 5) shows that the samples fall mainly within the field II (kerogen Type III) and deposited under marginal dysoxic-anoxic conditions.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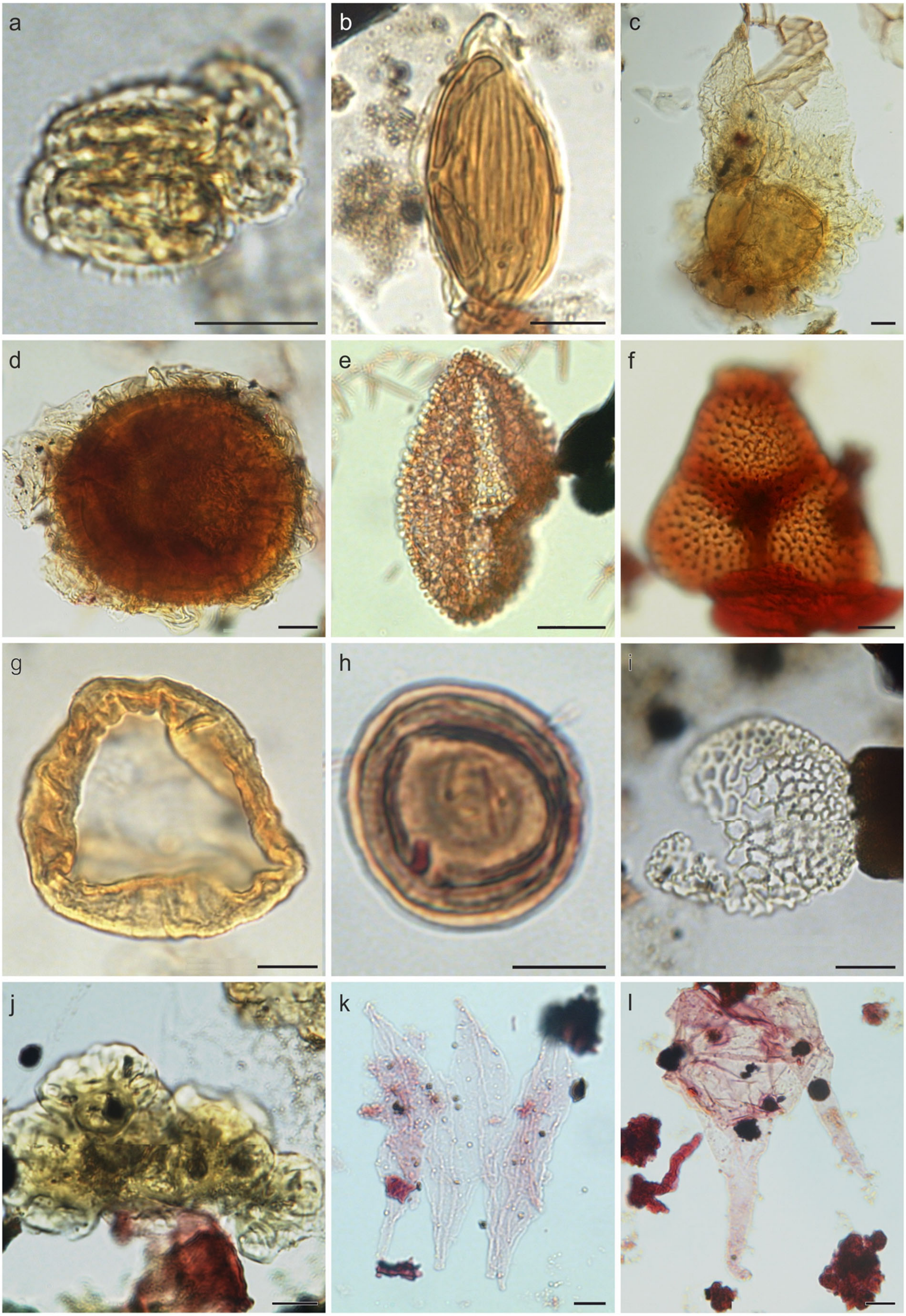
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◀ **Fig. 4** Scale bar is equal to 10 μm, **a** *Droseridites senonicus*, Hj-07_EF E 531, **b** *Equisetosporites ambiguus*, Hj-07_EF B342, **c** *Ariadnaesporites* sp., Hj-01_EF P262, **d** *Crybelosporites pannuceus*, Hj-16_EF H301, **e** *Stellatopollis* sp., Hj-16_EF B524, **f** *Integritetradites porosus*, Hj-10_EF O344, **g** *Inaperturopollenites* sp., Hj-16_EF N431, **h** *Classopollis* sp., Hj-16_EF U433, **i** *Afropollis* sp., Hj-16_EF N354, **j** Isolated coenobium of *Botryococcus* cf. *B. braunii*, Hj-02_EF Q323, **k** Isolated coenobium of *Scenedesmus* sp., Hj-06_EF Q351, **l** *Odontochitina operculata*, Hj-10_EF Q34-3

Abu Roash association

The palynofacies composition within the Abu Roash Formation (samples Hj-01 to Hj-09) seems to witness an abrupt variation from the underlying associations and comprises 60–85% AOM, 10–35% phytoclasts, and 3–13% palynomorphs (Fig. 5), except for sample Hj-09 which has a low AOM (37%) and high palynomorph content (37%). AOM is characterised by yellow granular and fluorescent masses, seemingly of marine algal origin (Fig. 3a, b), similar to AOM type A of Thompson and Dembicki (1986). In addition, the free pyrite traces supplemented with high accumulations of AOM in the limestone intercalated with shale of the Abu Roash Formation (samples Hj-01 to Hj-09; e.g. Figure 4c, d) indicate a distal reducing (suboxic-anoxic) setting deposited under a low rate of sedimentation (Einsele 1992; Tyson 1995; Mahmoud et al. 2017). Phytoclasts including mainly wood and cuticles are strongly diluted with opaques. Palynomorphs are generally rare-common and represented by marine elements, predominantly dinocysts and rare microforaminiferal test linings (Appendix 1). However, this association witnesses an exceptional dominance and high abundance of the coccalean algae *Pediastrum* and its allies mainly *Botryococcus* and *Scenedesmus* (El Atfy et al. 2017) (Fig. 3a, b). Such a record argues for brackish to fresh water influxes (Tappan 1980). *Pediastrum* is found to be common to abundant in the Abu Roash and overlying Khoman formations and occurs intermittently in the Bahariya and Kharita formations (e.g. El Beialy 1994). This event was considered a reliable ecological datum that marked the late Cenomanian-early Turonian in the north Western Desert (El Atfy et al. 2017 and references therein). Nevertheless, in the studied material, the age is adjusted younger due to the co-occurrence of the Coniacian-Santonian marker *Droseridites senonicus* within the same interval.

The Abu Roash Formation revealed a frequent record of the paleoperidinioidean dinocyst *Subtilisphaera*. This taxon

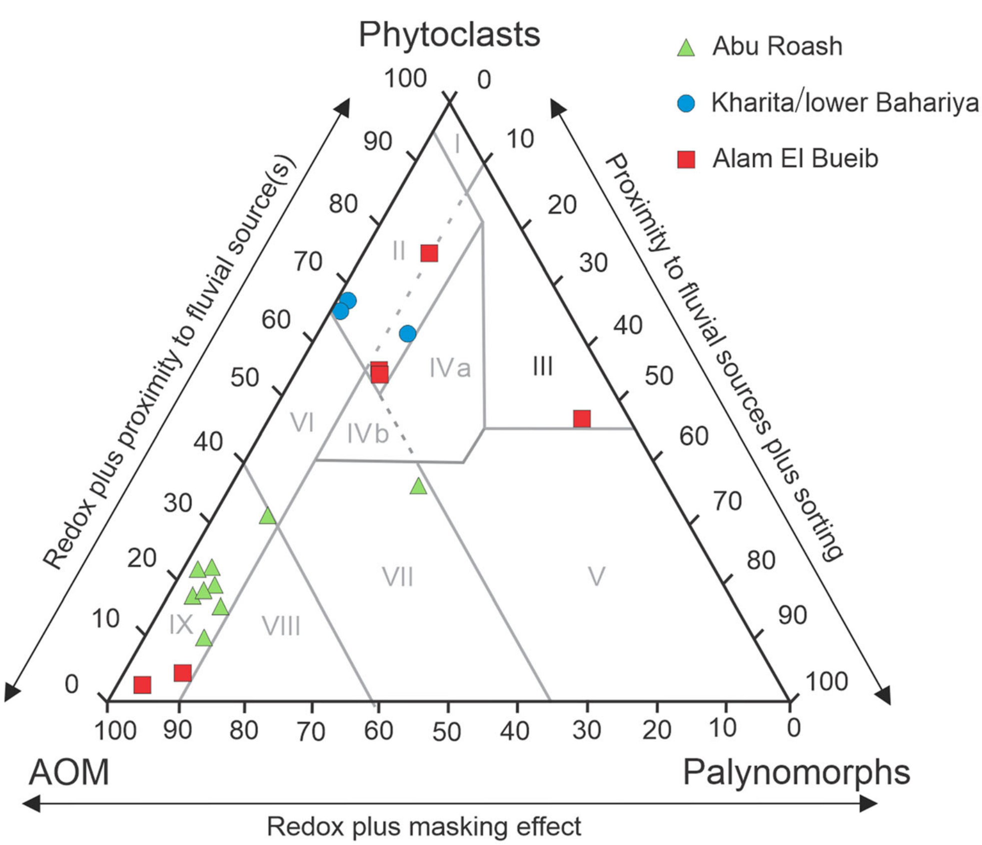

Fig. 5 APP ternary diagram (Tyson 1989) of the studied samples from the Faghur Hj5-1 well, Western Desert, Egypt; field I = kerogen Type III, field II = kerogen Type III, field III = kerogen Type III or IV, field IV = kerogen Type III or II, field V = kerogen Type III > IV, field VI = kerogen Type II, field VII = kerogen Type II, field VIII = kerogen Type II > I, field IX = kerogen Type II > I

has been linked to low-salinity marine palaeoenvironments in the Mid-Cretaceous of Senegal (Jain and Millepied 1975), inner- and middle-shelf conditions in the early to late Albian of Libya (Uwins and Batten 1988), and restricted marine conditions in the Aptian-Albian of Brazil where high abundances resemble brackish lagoonal facies (Carvalho et al. 2006).

Plotting of retrieved palynofacies particles on the APP ternary diagram reveals that Abu Roash Formation samples are located mainly within the field IX, except for sample Hj-09 which is located within the field VII. These fields correspond to kerogen Type II > I (highly oil-prone facies) and Type II (oil-prone facies), respectively, supporting a distal marine environment with suboxic-anoxic and dysoxic-anoxic conditions (Tyson 1995).

Discussion and interpretation

Age assignment and comparison with previous local palynofloral schemes

The investigated samples are cuttings and discussed down hole. Three distinct palynofloral assemblages have been categorized. Firstly, the Abu Roash Formation is dated as Turonian-Santonian, based on the co-occurrence of *Droseridites senonicus* (Fig. 4a), *Ariadnaesporites* spp. (Fig. 4c), and *Equisetosporites ambiguus* (Fig. 4b). *D. senonicus* is a key marker species in the Coniacian-Santonian of West Africa (Jardiné and Magloire 1965; Jan du Chêne et al. 1978), Coniacian of West Africa and South America (Mebradu 1982; Oláníyì Odébòdé 1987; Muller et al. 1987), Turonian-Santonian of intertropical Africa (Lawal and Moullade 1986; Salard-Cheboldaeff 1990), and Angola Basin (Morgan 1978) and the late Turonian-early Santonian of the Sudan (Awad 1994). In Egypt, it has been described from the Coniacian-Santonian of southern Egypt (Sultan 1985), late Turonian-early Santonian of the north Western Desert (e.g. Ibrahim et al. 2009; El Beialy et al. 2010; Ghassal et al. 2018), and Gulf of Suez (El Diasty et al. 2014). In addition, the co-existence of *Foveotricolpites giganteus* and *Foveotricolpites gigantoreticulatus* was detected, which were locally documented from early Turonian-Coniacian/earliest Santonian strata in different areas of Egypt (e.g. Schrank 1987, 1991; Schrank and Ibrahim 1995; El Beialy et al. 2010; Ghassal et al. 2018).

The palyniferous interval within the Kharita/lower Bahariya rock unit is dated as Cenomanian, based on the presence of *Integritetradites porosus* (Fig. 4f), which is considered a typical Cenomanian to late Cenomanian-early Turonian taxon in Egypt (e.g. Schrank and Mahmoud 2000; Ibrahim et al. 2009; El Beialy et al. 2010) and *Classopollis brasiliensis*. The latter taxon was described for the first time from the late Cenomanian of Senegal and Ivory Coast (Jardiné and Magloire 1965) and does not range above the late Cenomanian (El Beialy et al. 2010). A similar age could be deduced from dinocyst evidence based on the co-occurrence of *Odontochitina operculata* (Fig. 4l) and *Xiphophoridium alatum* (El Beialy et al. 2010 and records therein). Elsewhere in Egypt, this stratigraphic interval is characterised by elaterate pollen; however, none was found in the studied samples possibly for an as yet unknown ecological factor.

The Alam El Bueib Member is dated as Barremian, based on the occurrences of *Aequitriradites spinulosus*, *Dicheiropollis etruscus*, *Tucanopollis*, *Afropollis* column-*operculatus* group, *Stellatopollis*, and *Clavatipollenites hughesii*. *Aequitriradites spinulosus* is an index for late Barremian age (El Atfy et al. 2019b and records therein). *Dicheiropollis etruscus* is characteristic for the Neocomian-Barremian from the northern margin of Gondwana and other Tethyan realms (Penny 1986; El Atfy et al. 2019b and records therein).

According to the review of Schrank (1992), terrestrially derived pollen and spores are important for pre-Turonian palynostratigraphy, although marine dinocysts occur in some of the northern Egyptian localities and have occasionally been used in biostratigraphy. In the post-Cenomanian, there is a general break in the palynological record of the northern localities which results in scarcity or absence of palynomorphs. The large-scale flooding of the northeast African plate by the Campanian-Maastrichtian transgression caused the deposition of a black shale and phosphorite sequence with rich terrestrially derived and marine palynofloras in the middle latitudes of Egypt. The previous palynological contributions on the Egyptian localities are sufficient to postulate a reliable zonation.

The recorded assemblage from the Abu Roash Formation correlates well to the Turonian-Santonian Zone 7 of Schrank (1992) as well as Zones VI-VII of Schrank and Ibrahim (1995) and Zones IV-V of Ibrahim et al. (2009). Whereas the Alam El Bueib association is coeval to Zones 2a–2b of Schrank (1992), which is dated as Neocomian-Barremian and PZ II (late Hauterivian-early Barremian) of Mahmoud et al. (2019).

Palaeoenvironmental inferences

The interpretation of the palaeoenvironmental conditions prevailing during the deposition of the studied Cretaceous succession (in the Faghur Hj5-1 well) depends mainly on the results obtained from the APP ternary plot of Tyson (1989, 1995), as well as changes in palynomorph content. This is due to the fact that spatial-temporal variations in the composition of land plant communities are directly related to the environmental and climatic changes in the area where the plants lived. Consequently, palynomorphs and plant debris represent significant and reliable proxies to interpret palaeoenvironmental and climatic changes through time (Götz and Ruckwied 2014).

The sedimentary succession of the studied borehole starts at the base with the siliciclastic unit of the Alam El Bueib Member which was deposited generally in a shallow marine environment (Hantar 1990). The Alam El Bueib samples are situated within the palynofacies fields II and IX and one sample within field III (Fig. 5). Field II implies a deposition in marginal dysoxic-anoxic basin; field IX signifies a distal suboxic-anoxic basin, whereas field III refers to heterolithic oxic shelf (proximal shelf), based on low AOM preservation and abundant phytoclasts (Tyson 1995). Moreover, palynofacies particles distribution (especially in the lower part of the Alam El Bueib Member) is characterised by high abundance of degraded particles and opaque, equi-dimensional plant debris, due to transport. Pollen grains are rather abundant; AOM is less common. This may suggest that deposition might have taken place in the vicinity of an active fluvio-deltaic source.

Palynologically, the Alam El Bueib Member was dominated by miospores (mainly circumpoll pollen, such as *Classopollis* and *Circulina*) that are more numerous than marine elements. The few reported dinocysts are represented mainly by *Subtilisphaera* and *Oligosphaeridium* that reflect a marginal (brackish) shallow marine environment (Harding 1986). However, continental deposition cannot be excluded, as it was postulated by Keeley (1994) that a low Neo-Tethyan sea level in the Neocomian and Barremian (i.e. Alam El Bueib Member) contributed to extensive continental deposition on the unstable shelf (Fig. 1), where our study area is located.

Previous palynological results (e.g. Abdel-Kireem et al. 1996; Ibrahim et al. 1997; Mahmoud and Moawad 1999) reveal a near-shore to inner shelf shallow marine deposition for the Alam El Bueib Member, as indicated by the dominance of non-marine over marine palynomorphs.

The next event in the depositional history of the studied succession is the deposition of the Kharita/lower Bahariya interval. This interval is interpreted as being deposited in a marginal dysoxic-anoxic basin based on its location within field II of the APP plot. This environment is characterised by high concentration of phytoclasts which dilutes AOM (Table 1). This indicates that this interval was deposited in a proximal, near-shore shallow marine to deltaic environment where an admixture of terrestrial and marine organic matter has occurred. This interpretation agrees with previously studied sections in the Bahariya Formation in the north Western Desert (e.g. Ibrahim et al. 2009; Ghassal et al. 2018 and references therein).

The studied section ends with the deposition of the Abu Roash Formation. The Abu Roash samples are located within field IX which represents deposition in a distal suboxic-anoxic basin; the only exception is sample Hj-09 which is located within field VII implying deposition in a distal dysoxic-anoxic shelf. AOM is the dominant organic component in a dysoxic to anoxic depositional environment and increases with increasing nutrient availability and decreasing oxygen in the waters (Tyson 1995). A similar scenario for the deposition of the Abu Roash Formation was suggested by Mahmoud et al. (2017).

However, an exceptional dominance and high abundance of freshwater algae (mostly *Pediastrum*) are of special significance (Table 1). In such marine sediments, *Pediastrum* represents an allochthonous component carried in by rivers and streams from freshwater catchment areas (Brenac and Richards 2001). El Atfy et al. (2017 and references therein) considered this algal proliferation a reliable ecological datum that marks the late Cenomanian-early Turonian in the north Western Desert. They assumed that the occurrence of *Pediastrum* and other algae in such marine deposits reflects the predominant deposition of fluviatile sediments related to the discharge of rivers into shelf seas. Previous records of these algae (see discussion in El Atfy et al. 2017) support the local nature of this ecozone within the northern part of the Western Desert**.** The high number of freshwater algae and the abundance of AOM within the studied succession of the Abu Roash Formation may be related to high terrestrial influx of freshwater algae brought by river or delta systems.

To sum up, the results of APP plotting (sensu Tyson 1989, 1995) tell that most of the studied samples (i.e. Abu Roash and few samples from the Alam El Bueib) represent sedimentary facies deposited distally on the shelf (fields IX and VII). Only the Kharita/lower Bahariya interval and four samples from the Alam El Bueib represent facies deposited proximally or marginally on the shelf (fields II and III).

Palynofloral provincialism and palaeoclimate

Generally, pollen and spores could potentially outline the floral provinces and offer reliable evidence for palaeobiogeography and palaeoclimate. The recorded palynomorphs from the studied Alam El Bueib Member are indicative of the Early Cretaceous (pre-Albian) *Dicheiropollis etruscus*/*Afropollis* Phytoprovince of Herngreen et al. (1996) and its equivalents sharing the following characteristics:

- Predominance of *Classopollis*
- Well-represented gymnospermous pollen *Araucariacites*/*Inaperturopollenites*
- Presence, although rare, of the gymnosperm pollen *Eucommiidites*
- Spore genera mainly dominated by psilatrilete taxa (e.g. *Concavisporites* and *Gleicheniidites*), as well as by *Cicatricosisporites* and *Aequitriradites*, and sporadically by some other forms
- The occurrence of stratigraphically-relevant taxa, in a stratigraphic order *Dicheiropollis etruscus*, *Tucanopollis crisopolensis*, *Afropollis* spp.

Palaeoclimate within the (pre-Albian) *Dicheiropollis etruscus*/*Afropollis* Phytoprovince was interpreted as being arid (Herngreen et al. 1996). This province, initially defined based on palynological data from the palaeoequatorial area of western Africa and eastern South America, is dominated by Cheirolepidiaceae (*Classopollis*) pollen and has a high abundance of ephedralean pollen, but only few pteridophyte spores occur (Herngreen et al. 1996). Furthermore, the abundance of *Classopollis* (cheirolepidiacean conifer) implies that the pollen grains are derived from cheirolepidiaceous-dominated vegetation, able to tolerate dry conditions (Batten 1982). As a thermophilous taxon, it also indicates warm to subtropical climatic conditions (Lindström and Erlström 2011) and can adapt to arid conditions (Mahmoud et al. 2017). In addition, *Dicheiropollis etruscus* (Cheirolepidiaceae) was used by Doyle et al. (1982) as a marker of arid climate during the Barremian-Aptian period. Cheirolepidiaceae were widespread in coastal environments at low to mid-palaeolatitudes especially during the Cretaceous (Lupia et al. 1999). They were particular constituents of low diversity floras growing under semi-arid Mediterranean-type-like palaeoclimates (Steart et al. 2014). A similar palaeoclimate preference is also assumed for some ephedroids in comparable Cretaceous assemblages. The numerous occurrences of *Classopollis* in the studied material, sometimes as tetrads, imply that their parent plants were important components of the coastal marshes (Abdel-Kireem et al. 1996 and citations therein). The humid conditions inferred by the common occurrence of hygrophilous palynomorphs (e.g. *Deltoidospora* and *Cicatricosisporites*) reflect pteridophytic vegetation that grew on moist biotopes under fairly more local humid conditions (El Beialy et al. 2011). The palaeoclimate of this interval within the north Western Desert was previously interpreted as being tropical but semi-arid (Abdel-Kireem et al. 1996). Recently, El Atfy et al. (2019b) found higher abundances of humidity indicators compared to aridity indicators for the Alam El Bueib Member, indicating that a humid climate prevailed in the northern Western Desert during the late Hauterivian-early Barremian time. In summary, the palaeoclimate during the deposition of the Alam El Bueib Member is characterised as warm and semi-arid and perhaps with local humid conditions.

In the present material, some components from the Kharita/lower Bahariya interval have been dated as Albian-Cenomanian, as discussed earlier. Within this rock unit, it is unexpected that representatives of *Afropollis* pollen are rare, and elaterates are completely missing. Such an absence of those crucial taxa has been previously documented (e.g. Schrank and Mahmoud 1998, 2000). Elaterates are indicative elements in many synchronous Albian-Cenomanian sections worldwide (see Herngreen et al. 1996). Their absence from Egyptian rocks was first interpreted by Schrank (1992) as being related to palaeoecological factors or to a still inadequate database. Later, Schrank (2001) noted that *Afropollis* (aff. Winteraceae) and elaterate producers are mainly inhabitants of palaeotropical humid coastal plains.

The palynomorphs from the Abu Roash Formation could belong to the Senonian Palmae Phytogeographic Province of Herngreen et al. (1996), but due to limited samples and low frequency of palynomorphs, it is not possible to recognise it here. However, the presence of *Ariadnaesporites* (aquatic plant), *Gabonisporis vigourouxii*, *Zilvisporis blanensis*, *Proteacidites*, and *Retimonocolpites* as characteristic taxa of this province implies a warm-humid climate (Herngreen et al. 1996) for the Abu Roash Formation.

Hydrocarbon source potential

The current palynofacies concept is in many ways equivalent to that of organic facies, which represents bulk organic geochemistry in the sediments. However, based on the optical investigation of organic particles in the sediment, palynofacies analysis provides more parameters than bulk geochemical data and allows interpreting the changes in the sedimentary environment based on high variety of parameters. Palynofacies data also provide direct information on the biological sources and constituents of the particulate organic matter assemblages; therefore, palynofacies analysis is used as an aid in petroleum source potential interpretations (Roncaglia and Kuijpers 2006 and references therein). For the purpose of this study, palynofacies analysis helps greatly in interpreting kerogen quality and maturity as below:

Kerogen type (quality)

The kerogen composition of each one of the studied rock units reflects a mixture of two major organic matter contributors, AOM and phytoclasts. Within the Alam El Bueib Member, the recorded AOM implies mostly gas-prone kerogen (Thompson and Dembicki (1986). Phytoclasts are those broken-up terrestrial macrophytes like wood fragments, cuticles, cortex tissues, and oxidized plant particles (opaques). They make up the bulk composition of kerogen types III and IV. Plotting of retrieved palynofacies particles on the APP ternary diagram shows that Alam El Bueib samples are located mainly within fields II and IX with one sample in field III (Fig. 5). Fields II and III imply kerogen Type III and III or IV (gas-prone); a similar result (kerogen Type III) is obtained from the Kharita/lower Bahariya interval (Fig. 5), whereas field IX refers to Type II > I kerogen (highly oil-prone). The identified AOM from the Abu Roash Formation refers mostly to AOM type A of Thompson and Dembicki (1986), which suggests oil-prone kerogen. High AOM concentrations infer the presence of a kerogen Type I or II (Tyson 1995). APP plot (field IX; Fig. 5) supports this kerogen typing for the Abu Roash Formation, i.e. Type II > I kerogen.

In summary, palynofacies results show that the studied material comprises two distinct facies of kerogen (Fig. 5). First, Type II > I kerogen (AOM-rich) is overwhelmingly dominant in the Abu Roash Formation and a few samples from the Alam El Bueib Member and is presumed highly oil-prone, whereas Type III kerogen (phytoclast-rich) is particularly influential in the Alam El Bueib Member and Kharita/lower Bahariya unit and considered gas-prone.

Thermal maturity

For the purpose of estimating the thermal maturity of the studied samples, optical examination of spore and pollen exine in transmitted light microscopy has been employed. Maturity data follows Hartkopf-Fröder et al. (2015), exine colours of Pearson (1984), and spore colour index (SCI) numbers and vitrinite reflectance after Marshall and Yule (1999) that correspond to the numerical scale thermal alteration index (TAI) of Staplin (1969). The measured smooth-walled palynomorphs from the Alam El Bueib Member show yellow to pale brown colour, SCI values from 4 to 8 (TAI 2 to 3) almost equivalent to 0.5 to 1.3% vitrinite reflectance (VR), indicating immature to mature stage (Fig. 2). Different thermal maturity stages are present, which could be attributed to the fact that the source rock contains transported organic matter.

The colour of palynomorphs' exine from the Kharita/lower Bahariya unit varies between pale and medium yellow (SCI 2-3), (TAI 1+ to 2-), equivalent to 0.3 to 0.5% VR and hence inferring an immature phase. Those palynomorphs recovered from the Abu Roash Formation display pale to dark yellow colour (SCI 2-4; TAI 1+ to 2), equivalent to 0.3 to 0.5% VR, suggesting an immature phase.

Conclusions

A comprehensive palynological and palynofacies study of 18 cutting samples representing the Alam El Bueib, Kharita/lower Bahariya and Abu Roash lithostratigraphic units in the Faghur Hj5-1 Well, north Western Desert, Egypt, has been carried out. The supplementation of palynological data with palynofacies analysis made the subsequent observations of special significance:

1. The Alam El Bueib Member (Hautervian-Barremian) was deposited in a shallow marine setting, under oxic proximal to distal shelf conditions. The overlying Kharita/lower Bahariya interval of Cenomanian age, was deposited in a shallow marine, dysoxic-anoxic basin. The Abu Roash Formation (Turonian-Santonian) was deposited in a distal suboxic-anoxic basin.
2. The Alam El Bueib Member (most of samples) and the Kharita/lower Bahariya succession belong to kerogen Type III (gas-prone), whereas the Abu Roash Formations and a few samples from the Alam El Bueib Member reveal Type II > I kerogen, which is oil-prone.
3. Thermal maturity determinations obtained from colour changes of smooth-walled palynomorphs reveal that Alam El Bueib samples belong to immature to mature stages however, Kharita/lower Bahariya, and Abu Roash samples are within the immature phase.

Acknowledgements The author is indebted to Prof. Maher El-Soughier (Aswan University) and the Egyptian General Petroleum Corporation (EGPC) for providing the samples and well log for this study. Dr. Rainer Brocke is gratefully acknowledged for running the fluorescence investigation of palynofacies samples and Prof. Alan Lord for improving the English of the manuscript. The author wishes to thank Mercedes di Pasquo, an anonymous reviewer and guest-editors Angela Bruch, Dieter Uhl, and Torsten Utescher for their insightful comments and constructive criticism as well as for their invitation to contribute to this special issue.

Funding The author acknowledges financial support by Alexander von Humboldt Foundation, Germany (EGY-1190326-GF-P).

Compliance with ethical standards

Conflict of interests The author declares that he has no conflict of interest.

Appendix 1

List of the recorded palynomorph taxa (arranged alphabetically), Faghur Hj5–1 well, Western Desert, Egypt.

I. Spores and pollen
I.I. Pteridophyte and bryophyte spores

Aequitriradites spinulosus (Cookson and Dettmann) Cookson and Dettmann 1961
Ariadnaesporites spp.
Cibotiumspora jurienensis **(**Balme) Filatoff 1975
Cicatricosisporites spp.
Concavisporites spp.
Concavissimisporites spp.
Crybelosporites pannuceus **(**Brenner) Srivastava 1977
Crybelosporites spp.
Cyathidites australis Couper 1953
Deltoidospora spp.
Dictyophyllidites spp.

Duplexisporites generalis Deak 1962
Duplexisporites spp.
Gabonisporis vigourouxii Boltenhagen 1967
Gleicheniidites senonicus Ross 1949
Gleicheniidites spp.
Murospora florida (Balme) Pocock 1961
Triplanosporites spp.
Zilvisporis blanensis

I.II. Pollen
Afropollis aff. *jardinus* Doyle et al. 1982
Afropollis jardinus (Brenner) Doyle et al. 1982
Afropollis kahramanensis Ibrahim and Schrank 1995
Afropollis operculatus Doyle et al. 1982
Afropollis spp.
Araucariacites australis Cookson 1947
Balmeiopsis limbatus (Balme) Archangelsky 1977
Callialasporites sp.
Circulina parva Brenner 1963
Classopollis brasiliensis Herngreen 1975
Classopollis classoides Pflug 1953
Classopollis spp.
Clavatipollenites hughesii Couper 1958
Dicheiropollis etruscus Trevisan 1972
Droseridites senonicus Jardiné and Magloire 1965
Ephedripites jansonii (Pocock) Muller 1968
Ephedripites spp.
Equisetosporites ambiguus (Hedlund) Singh 1983
Eucommiidites sp.
Foveotricolpites giganteus (Jardiné and Magloire 1965) Jan Du Chéne et al. 1978
Foveotricolpites gigantoreticulatus (Jardiné and Magloire 1965) Schrank 1987
Inaperturopollenites spp.
Integritetradites porosus Schrank and Mahmoud 2000
Nyssapollenites sp.
Proteacidites sp.
Retimonocolpites spp.
Stellatopollis spp.
Tucanopollis crisopolensis Regali 1989

II.Green and blue-green algae
Botryococcus spp.
Pediastrum spp.
Scenedesmus spp.
Tasmanites spp.

III. Miscellaneous
Microforaminiferal test linings

IV. Dinoflagellate cysts
Circulodinium spp.
Coronifera oceanica (Cookson and Eisenack) May 1980
Cribroperidinium edwardsii (Cookson and Eisenack) Davey 1969
Cribroperidinium spp.
Cribroperidinum orthoceras (Eisenack) Davey 1969
Florentinia spp.
Odontochitina operculata Deflandre and Cookson 1955
Oligosphaeridium spp.
Spiniferites spp.
Subtilisphaera spp.
Systematophora spp.
Trichodinium castanea (Deflandre) Clarke and Verdier 1967
Xiphophoridium alatum (Cookson and Eisenack) Sarjeant 1966

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