Geologia Croatica
Journal of the Croatian Geological Survey
and the Croatian Geological Society

2025 | 78/1 | 15–29 | 10 Figs. | 2 Tabs. |

www.geologia-croatica.hr

Albian biostratigraphy and palaeoecology of the Sharib-1X borehole (northern Egypt): Insights from palynomorphs and palynofacies

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doi: 10.4154/gc.2025.02

Article history:
Manuscript received: January 30, 2024
Revised manuscript accepted: October 08, 2024
Available online: February 26, 2025

Abstract

Well-preserved terrestrial palynoflora assemblages, dominated by pteridophyte spores (e.g., *Deltoidospora*, *Triplanosporites*, and *Dictyophyllidites*), with angiosperms and elaterate-bearing taxa, were recorded from the Kharita Formation, northern Egypt. Biostratigraphically, the angiosperm pollen *Afropollis jardinus* is the most significant element, along with elaterates including *Elaterosporites klaszii* and *Elaterocolpites castelainii*, in dating the Kharita Formation and confirming its previous (dinoflagellate) Albian dating. We applied current and previous documented redox states in the borehole and discovered evidence of missing of angiosperms and elaterates from some stratigraphic levels. At stratigraphic horizons where opaque phytoclasts are extraordinarily abundant, oxidation is highly expected and, consequently, some palynomorphs of the original palynological assemblages may have been oxidized. At other horizons with mild oxidation, some palynomorphs cannot be preserved due to environmental restrictions. Under these circumstances, if these marker taxa are missing, age assessments can be unreliable. Therefore, care must be taken in order to determine reliable palynostratigraphy. An oxic to dysoxic-suboxic marginal marine environment was inferred, with a few examples of periodic distal settings at the basal and top parts of the Kharita Formation. The Kharita palynofloras, as part of the palynofloristic Albian-Cenomanian African-South American (ASA) province, reflect the influence of the break-up of the continents of Africa and South America. They reflect the resultant global palaeoclimate change near the equator, which brought humid conditions to Egypt during Albian times.

Keywords: palynomorphs, Kharita Formation, Albian, marginal environment, Egypt

1. INTRODUCTION

The studied Sharib-1X borehole (Lat. 30° 11' 36'' N and Long. 28° 19' 06'' E) is located east of the Qattara Depression in the northern Western Desert (Fig. 1), as a part of the unstable shelf of Egypt. The borehole lies at the Ras Qattara ridge (Sharib-Sheiba High), which marks the southern boundary of the Abu Gharadig Basin. Here, productive oil and gas fields were discovered (see SAAD et al., 2023). The borehole was palynologically investigated by OMRAN et al. (1990), in which the original stratigraphy (WEPCO, 1971, taken from the stratigraphic log), was revised based on dinoflagellate cysts, recorded from five samples (depths 2124, 2023, 1950, 1868, 1858 m, respectively). Other contributions such as SCHRANK & IBRAHIM, 1995; MAHMOUD & DEAF, 2007; TAHOUN & IED, 2019; DEAF et al., 2020; MANSOUR et al., 2021; MAHMOUD et al., 2023) constrained this interval to the middle-upper Albian. ZOBAA et al. (2013) investigated an interval from the same borehole (depths from 1874 to 1633 m) and dated a carbonate interval (depths from 1874 to 1837 m) as middle to late Jurassic (Masajid Fm) in age, based on dinoflagellate cysts. Their spore and pollen association lacks the angiosperms and the elaterates. Here, we investigated deeper downhole sediments, at depths from 2078 m to 1850 m. In light of the recently published spores and pollen information in Egypt, see the comprehensive literature listing in SOLIMAN & EL ATFY (2023), we documented an unequivocal terrestrial Albian association with angiosperms and elaterates. These data offered a unique opportunity to revise the age assessments of the borehole. OMRAN et al. (1990) suggested a proximal (restricted) to inner-shelf environment for the Kharita Formation (Albian) in the Sharib-1X borehole. They noted that the sea gradually shallowed to the south, to reach the area of the borehole during the Albian.

Oxidation of the palynological organic matter is known to occur during transport (e.g., TYSON, 1995; BATTEN, 1996). The impact of such oxidation on the selective preservation of terrestrial palynomorphs can only be depicted by looking at the total palynofacies. For instance, if the palynofacies is dominated by opaques, this would mean that, at least, part of the recorded palynomorphs may have oxidized. The impact of oxidation can be clearly seen from the occurrence of, for instance, lath-shaped opaque phytoclasts. In this case, the amorphous organic matter (AOM), together with sensitive palynomorphs, would oxidize more readily than the phytoclasts and, consequently, disappear from the palynological content. Laboratory oxidation techniques, avoided herein (e.g., acetolysis; nitric acid treatment), are also known to cause physical degradation to spores and pollen associations (e.g., JARDINÉ

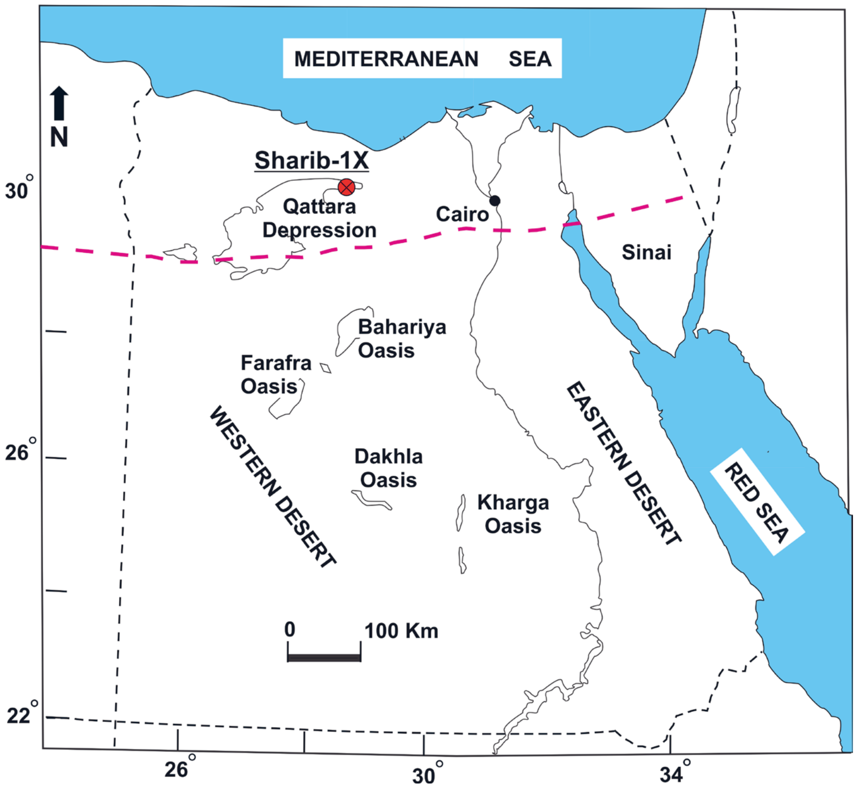

Figure 1. Geographical map of Egypt showing the location of the investigated Sharib-1X borehole.

et al., 2015). However, SCHRANK (1988) stated "After oxidation with cold HNO_3 and subsequent alkali (KOH or NH_4OH) treatment, an expansion of the periphragm was observed". He also noted that after excessive oxidation most dinoflagellates are eliminated. Even so, the impact of degradation on selective sporomorph species by excess oxygen in depositional basins is not, to our knowledge, described as being the same as for dinoflagellates. For dinoflagellates, in cases of excess O_2, sensitive (heterotrophic) species are more susceptible to post-depositional degradation than autotrophic ones (e.g., ZONNEVELD et al., 2007).

We are interested in investigating the palynomorph composition of the Kharita Formation, Sharib-1X borehole, for biostratigraphic and palaeoenvironmental implications. We intend to apply land-derived palynomorphs to offer an additional palynological age assessment of the Albian interval of the well, which was previously dated on the basis of dinoflagellate cysts (OMRAN et al., 1990). We are also interested in providing insights into understanding terrestrial palynomorph degradation and its impact on reliable palynological age assessment. We also aim to study the palynofacies constituents of the investigated Albian interval of the borehole and their importance in understanding the palaeoenvironment and its redox states. Among our objectives is the correlation of the Albian miospores association with other contemporaneous counterparts from additional geographically-related vegetation provinces in the African and South American continents. We also compare these miospores with other areas worldwide.

2. GEOLOGICAL SETTING

The northern Western Desert has a spectacular subsurface geology. This northern segment of the African Platform is made up of thick sedimentary, Cambrian to Holocene, layers that gradually slope seaward. Most of this area is blanketed by Miocene deposits, whereas along the Mediterranean coast, limited Pliocene shales and sandstones are exposed. Many petroliferous rift basins, developed during the Mesozoic fragmentation of Gondwana and the opening of the southern Neo-Tethys, formed in northern Egypt (e.g., TASSY et al., 2015). These basins are often aligned in half-grabens-oriented E-W, NE-SW and ENE-WSW directions (GUIRAUD et al., 2005). Structurally, the northern Western Desert belongs to the "Unstable Shelf" of SAID (1962), which was tectonically active during most of the Phanerozoic; subsidence, uplift and basin inversion occurred (HANTAR, 1990; EL ATFY, 2021). The thickest of the Phanerozoic layers occur in the Abu Gharadig Basin (8-9 km thick), while it may only reach as little as 3 to 6 km elsewhere (HANTAR, 1990). The Western Desert in general is defined by a northwestward thickening Palaeozoic sequence and a northward thickening prism of Mesozoic and Palaeogene strata. The east-west trending Sharib-Sheiba high forms a regional uplift that divides the southern and coastal northern Western Desert basins, whereas the examined borehole is located at the northern boundary of this trend, indicating that sediments were deposited in shallower settings (E.G.P.C., 1992). A generalized stratigraphic column of the Cretaceous rock units in the Western Desert modified after BOSWORTH & TARI (2021) is presented in Figure 2.

In the Shushan Basin, to the north of the investigated borehole, the palynological dating showed that Lower Cretaceous (Hauterivian to Albian) sediments overlie the Jurassic strata (see MAHMOUD et al., 2023). Southward, where the Sharib-1X borehole lies, the Hauterivian to Aptian sediments gradually disappear (OMRAN et al., 1990). The regionally widespread

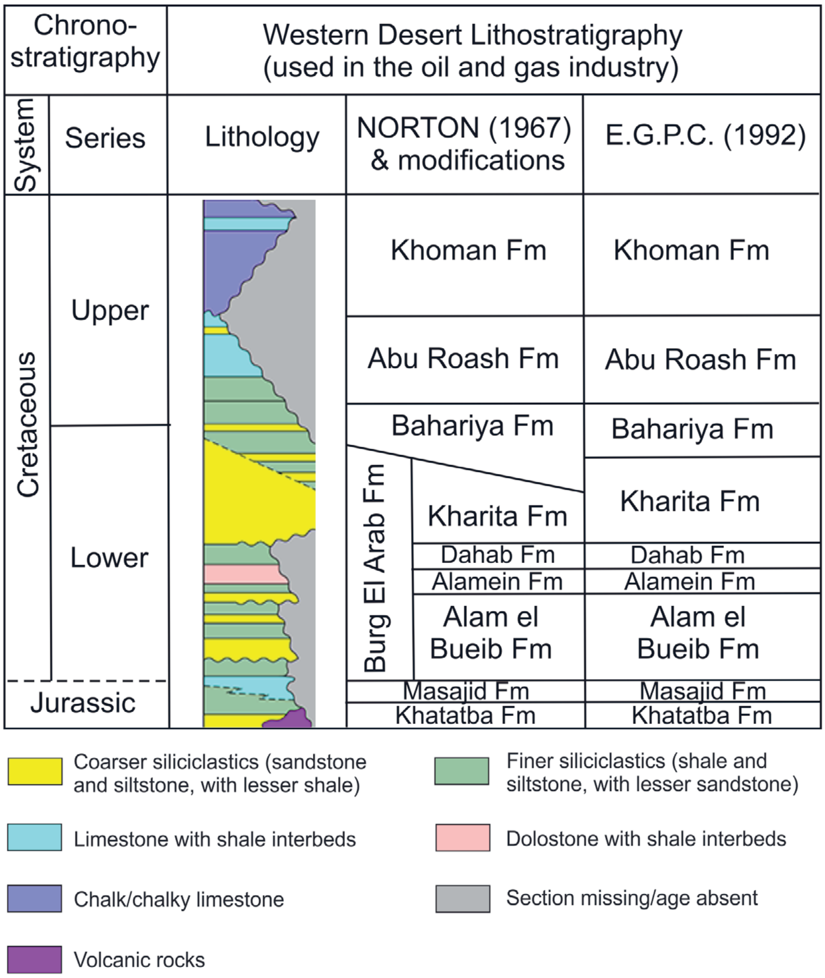

Figure 2. Generalized stratigraphic column showing the main Cretaceous rock units in the northern Western Desert of Egypt (Modified after BOSWORTH & TARI, 2021).

Aptian carbonate units, in the northern Western Desert, known as the Alamein Formation, in addition to the Dahab Formation, are missing at the Sharib-Sheiba high, where the Sharib-1X borehole is located (OMRAN et al., 1990). Therefore, the Albian Kharita Formation directly overlies the middle Jurassic (?Bajocian–Callovian) sediments (OMRAN et al., 1990). This pronounced and significant hiatus means that the Alamein carbonates were not deposited in the study area due to uplifting that was initiated during the Middle Jurassic (BAYOUMI & LOTFY, 1989; MESHREF, 1996). This gap seems to have highly impacted the chronostratigraphy of the Lower Cretaceous Sharib-1X borehole, as seen from previous controversial age assessments (WEPCO, 1971; OMRAN et al., 1990; ZOBAA et al., 2013).

3. LITHOSTRATIGRAPHY

The studied Kharita Formation consists mainly of sandstones with fining upward sequences. Shale and thin limestone streaks are sporadically interbedded with sandstones. Thicker sandstone with shale intercalations occurs in the lower part of this unit. It unconformably overlies the Alamein Formation (GHORAB et al., 1971; SAID, 1990; E.G.P.C., 1992). The sandstones, siltstones and limestones of the overlying Bahariya Formation (NORTON, 1967) cover large areas in the subsurface of the Western Desert and rest, sometimes unconformably, on the Kharita Formation. The type section of the Kharita Formation is placed between 2890 and 2501 m in the Kharita-1 borehole. The maximum thickness of this unit was reported from the northernmost deeper basins (Matruh-1 borehole, 1100 m). The upper part of the Kharita Formation is made up of clean coastal plain sandstone with shale and silt interbeds (SCHLUMBERGER, 1984), whilst the basal level is made up of finely laminated shallow marine sandstone, siltstone, and shale intercalations. In the Sharib-1X borehole, this rock unit is characterized at the base by coarse-grained mildly calcareous sandstone of varied colours, which are interbedded upwards with greenish to dark grey fissile calcareous shale. According to palynological evidence, the Kharita Formation dates from the early to middle Albian (ABOUL ELA & TAHOUN, 2010; TAHOUN, 2012; TAHOUN et al., 2012, 2015; GENTZIS et al., 2018; TAHOUN et al., 2018; GENTZIS et al., 2019). The formation was interpreted to reflect a high-energy and regressive shallow marine environment (e.g., OMRAN et al., 1990; E.G.P.C., 1992; SCHRANK & IBRAHIM, 1995; DEAF et al., 2014; EL ATFY et al., 2019; GENTZIS et al., 2019; MAHMOUD et al., 2019).

4. MATERIAL AND METHODS

Eleven cuttings samples, collected from the Kharita Formation (Albian) of the Sharib-1X borehole (Fig. 3) were palynologically

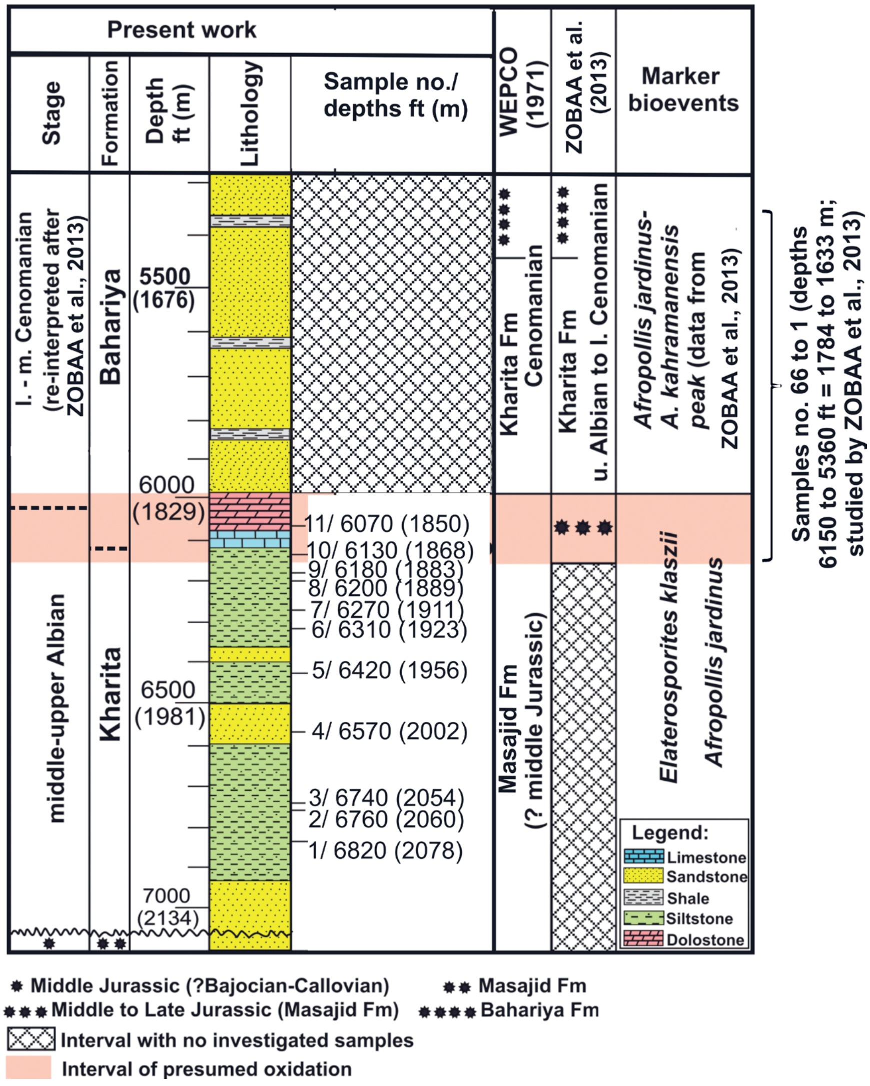

Figure 3. Lithological column of the Sharib-1X borehole, showing the positions of the studied samples, previous palynologically investigated intervals by ZOBAA et al. (2013) and the original stratigraphy (WEPCO, 1971).

investigated in this study using cold acid maceration. They were collected at depths from 2078 to 1850 m. About 20 grams were digested according to traditional laboratory processing techniques (e.g., PHIPPS & PLAYFORD, 1984; TRAVERSE, 2007). Samples were first treated with hydrochloric acid (HCl 32%) to remove carbonates ($CaCO_3$) and then washed several times with distilled water until neutralized. This was followed by maceration in hydrofluoric acid HF (40%) to dissolve silicates and then washed again several times until neutralized. After the digestion was completed, residues were then sieved using a 15 μm nylon screen. Ultrasonic vibration, acetolysis, nitric acid treatment as well as any other treatment by oxidizing agents were avoided to protect the organic matter from breaking down or decomposing. This residue was used in palynofacies analysis. Part of the residue was treated by mild ultrasonic vibration for a few seconds to concentrate palynomorphs. Three to five slides from each sample, prepared with glycerin jelly as a mounting medium, were examined under light microscopy. Samples were examined using an Axiolab transmitted white light microscope at various magnifications to conduct semi-quantitative studies of organic matter, with photomicrography using its digital camera.

Approximately 250 specimens of different palynomorphs were counted, with the calculation of the relative percentages of palynomorph groups (Table 1). Another set of 500 total palynological organic matter (TPOM) particulates was counted to express the relative abundances of the total recorded palynofacies components (Table 2). The AOM-Phytoclasts-Palynomorphs (APP) ternary plot of TYSON (1995) is used primarily to infer the redox conditions. The ratio of marine to continental palynomorphs (m/c ratio) is also applied to assist in the discrimination between proximal and distal settings. It was calculated; using the count set of palynomorphs, by dividing the total number of counted marine palynomorphs by the total count of palynomorphs in every sample and then multiplying by 100.

5. RESULTS

All samples were productive, giving low to moderate palynomorphs with low diversity and moderate abundance. The preservation of organic materials is often moderate. The marine: continental ratio (m/c ratio), the relative abundance of major palynomorph groups, and the rela-

Table 1. Counts of the recorded palynomorphs in the investigated Albian interval of the Sharib-1X borehole. These data were used in the construction of the semi-quantitative distribution of sporomorphs, in the graphic presentation of palynomorph groups and palynomorph groups and in the synthesis of the SMP ternary diagram of DURINGER & DOUBINGER (1985).

Age/Stage	Middle-upper Albian										
Formation	Kharita										
Sample no.	1	2	3	4	5	6	7	8	9	10	11
Depth ft (m)	6820 (2078)	6760 (2060)	6740 (2054)	6570 (2002)	6420 (1956)	6310 (1923)	6270 (1911)	6200 (1889)	6180 (1883)	6130 (1868)	6070 (1850)
Spores											
Triplanosporites spp.	12	17	23	18	28	23	26	20	20	15	15
Deltoidospora hallii		9	16	14	17		13	11	11		10
Dictyophyllidites harrisii	9			10		12	15	10		12	8
Cicatricosisporites spp.	11		6			9		8	10		10
Deltoidospora australis				13	22	13				10	13
Deltoidospora spp.		17	30	28	31	29	27	#	31	15	10
Dictyophyllidites spp.	8	8	13	16		11		9	10		7
Concavissimisporites spp.				13					14		10
Deltoidospora toralis		9	19	13		15				9	9
Gemmatriletes sp.	8	12			15			9	12	10	8
Matonisporites sp.	10	13	18	17		13				11	
Biretisporites potoniaei			15		16	10				9	
Gleicheniidites senonicus	9					10	11	8		9	
Gleicheniidites feronensis		10							9	4	
Crybelosporites pannuceus						11				5	
Auritulinasporites intrastriatus				15			9	12	8	4	
Converrucosisporites sp.									1		
Concavissimisporites variverrucatus						14		5			
Cibotiumspora jurienensis				11			7	5			
Murospora sp.		6				9					
Densoisporites sp.						1					
Microfoveolatisporites sp.					1						
Gymnosperm pollen											
Callialasporites trilobatus		13			27	11	12	12		7	5
Callialasporites turbatus							11		7		5
Cycadopites spp.	12	23	20	15	11	9	15	10	15		25
Inaperturopollenites undulatus	9	13			4	4		10			24
Arucariacites australis	24	40	35	23	25	13	20	20	19	15	54
Balmeiopsis limbatus							9		8		10
Classopollis classoides	15		12	12	11	7	11	10		10	
Exesipollenites sp.			12	10			12	10		10	
Monosulcites sp.								1			
Bennettiteaepollenites regaliae							10	10	7		
Bisaccate pollen		5			11			10			
Classopollis sp.				10	10						
Taxodiaceaepollenites sp. 1	1										
Elaterate pollen											
Elaterocolpites castelainii											2
Elaterosporites klaszii	1	1	3		2	4	4				
Elaterosporites acuminatus		1									
Angiospem pollen											
Afropollis jardinus				7	2				7	10	
Retimonocolpites ghazalii										1	
Retimonocolpites sp.					2			3	2	4	
Monocolpopollenites sp.	4							3	2		
Afropollis aff. *jardinus*			10		4			4			
Monocolpites spp.	10	5	11				13	10			
Total sporomorphs	143	202	243	245	239	229	225	235	193	170	225
Total marine palynomorphs	105	41	5	5	11	6	25	15	55	80	17
Total palynomorphs	248	243	248	250	250	235	250	250	248	250	242

🟥 Barren of angiosperm pollen

tive abundances of the main total palynological organic matter (TPOM) components are presented graphically (Fig. 4). In the majority of samples, the m/c ratio (Fig. 4A) reflects values from 2:98 (sample 4, depth 2002 m) to a maximum of 16.9:83.1 (sample 2, depth 2060 m). At three horizons, marine dinocysts and/or foraminiferal linings reach percentages up to 73%, 28%, and 47% of total palynomorphs (samples 1, 9, and 10, depths 2078, 2493 and 1868 m) respectively. At these stratigraphic levels, the m/c ratio shows the highest values between 22.2:77.8 (sample 9, depth 1883 m) to 42.3:57.7 (sample 1, depth 2078 m).

Terrestrial pollen and spores are the dominant palynomorphs across the whole investigated borehole interval. They reach up to 98% of the total palynomorph content (sample 4, depth 2002 m). Among the spores, the pteridophyte ferns (Fig. 4B) are the most abundant (up to 76.6%, depth 1923 m). The lowest relative percentage of these ferns was recorded in sample 1 (27% of total palynomorphs, depth 2078 m). They are mainly represented by the smooth (sub) triangular forms of the genera *Deltoidospora*, *Triplanosporites*, and *Dictyophyllidites*. Ornamented (e.g., *Converrucosisporites*) and other spores such as *Densoisporites* are rare. Gymnosperms (mainly *Callialasporites*, and *Classopollis*) are common (up to 50.8% of total palynomorphs, sample 11, depth 1850 m). The bisaccate pollen and the elaterates are accessory components. They show sporadic lower relative percentages (up to 2.1% sample 2, depth 2060 m and 1.2% sample 3, depth 2054 m, of total palynomorphs). The angiosperms are represented by *Afropollis jardinus*, *Afropollis* aff. *jardinus*, *Retimonocolpites ghazalii*, *Monocolpopollenites* sp. and *Monocolpites* spp. These angiosperms, together with the above mentioned elaterates, are the most significant from a biostratigraphic point of view. They comprise up to 8.5% of the total palynomorph content (sample 3, depth 2054 m). Two samples lack angiosperms; the lowest relative percentage is 2% (sample 2, depth 2060 m).

The predominant constituents of the TPOM are brown wood whereas cuticles, membranous tissues, tracheids and resin are minor (Fig. 4C). The brown phytoclasts and the opaques constitute the overwhelming majority of the palynofacies. They reach up to 74.2% of total palynofacies (sample 3, depth 2054 m). The brown phytoclasts and the opaques are usually equidimensional in outline, but lath-shaped particles were also observed. The AOM is not as abundant as phytoclasts. At two levels, samples 1, depth 2078 m and 4 (depth 2002 m), it forms 22% and 36.8% of the total palynofacies, respectively. The palynomorph abundances do not show the same trend as the AOM. Samples 4 (depth 2002 m) and 10 (depth 1868 m) have the highest percentages of palynomorphs (33% and 35.8% of total palynofacies, respectively). A striking observation of

Table 2. Counts of the different palynofacies categories in the Sharib-1X borehole. This data was used in the synthesis of the APP ternary plot of TYSON (1993).

Age/Stage	Formation	Sample no.	Depth ft (m)	Amorphous organic matter (AOM)	Phytoclasts	Brown wood	Tracheidsa	Cuticles	Membranous tissues	Resin	Opaques	Ppalynomorphs	Spores	Pollen	Dinoflagellate cysts	Microforaminifera linings	Total palynofacies
Middle-upper Albian	Kharita	11	6070 (1850)	25		341	2	2	1	0	20		57	42	10	0	500
		10	6130 (1868)	27		235	5	9	5	0	40		55	39	25	60	500
		9	6180 (1883)	24		300	5	7	5	0	35		66	41	17	0	500
		8	6200 (1889)	30		235	10	12	6	2	35		75	70	25	0	500
		7	6270 (1911)	25		260	5	5	8	0	55		76	57	9	0	500
		6	6310 (1923)	15		274	3	3	9	0	60		83	49	3	1	500
		5	6420 (1956)	30		293	3	15	10	0	53		65	29	1	1	500
		4	6570 (2002)	184		130	3	3	5	0	10		95	68	2	0	500
		3	6740 (2054)	10		351	12	5	2	1	45		40	32	2	0	500
		2	6760 (2060)	15		280	5	5	10	0	60		57	51	17	0	500
		1	6820 (2078)	110		228	13	2	7	7	20		42	36	20	15	500

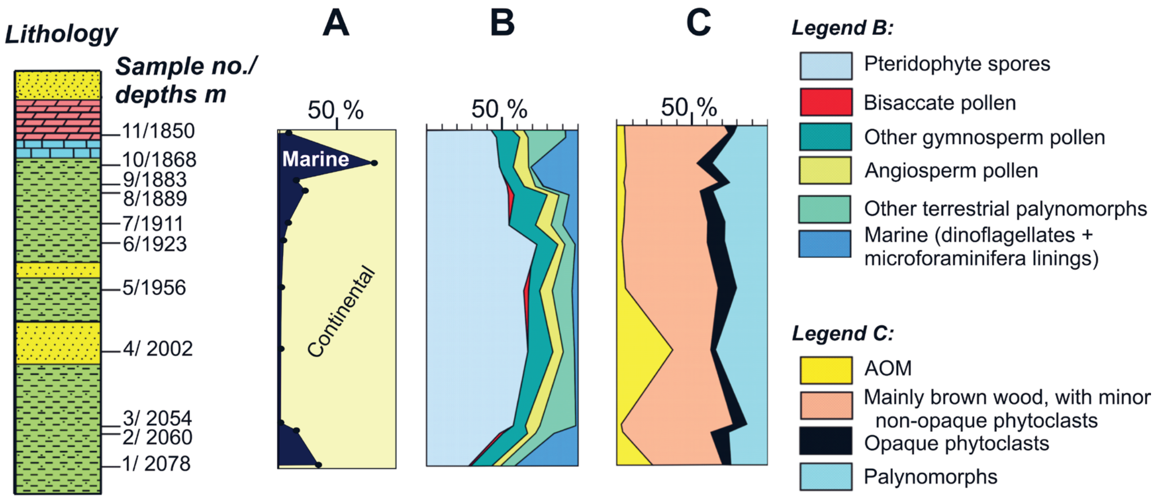

Figure 4. A) Marine to continental (m/c) ratio diagram; **B)** Percentage frequencies of the main palynomorph groups; **C)** Percentage frequencies of the main palynofacies categories.

our palynofacies is the lower relative percentages of the opaque particulates (maximum abundance of 12% of total palynofacies, sample 2, depth 2060 m).

The vertical stratigraphic distribution of the recovered spores and pollen grains, arranged by their highest occurrence (HO), is shown in Figure 5A. Details of the recovered dinoflagellate cysts, which were already previously recovered from the same investigated interval (MAHMOUD, 1989), are presented on Figure 5B.

6. DISCUSSIONS

6.1. Age assessment

In Africa, *Afropollis jardinus* was discovered from foraminifera-dated Albian samples of Senegal and Ivory Coast (JARDINÉ & MAGLOIRE, 1965; as S. CI. 156 Incertae Sedis), Gabon-Congo-Senegal (DOYLE et al., 1982) and Egypt (SCHRANK & IBRAHIM, 1995). This taxon was identified in Colombia from an ammonite bed of late Albian (to early Cenomanian) age (HERNGREEN & JIMENEZ, 1990). In northern South America, this taxon has been recorded from foraminifera-dated sediments of early Albian age in Brazil (HERNGREEN, 1973, 1975; REGALI et al., 1974; REGALI & VIANA, 1989) and Peru (BRENNER, 1968). The elaterates are known to enter the palynological record in the ancient northern Gondwana continent by the early Albian. *Elaterosporites klaszii* entered the stratigraphic records during the mid-Albian to the mid-Cenomanian in foraminifera-dated sediments from northern South America (MÜLLER, 1966; HERNGREEN, 1973; HERNGREEN & JIMENEZ, 1990) and Africa (JARDINÉ & MAGLOIRE, 1965; JARDINÉ, 1967; SCHRANK & IBRAHIM, 1995; TAHOUN et al., 2012; EL BEIALY et al., 2010; ZOBAA & OBOH-IKUENOBE, 2018; DEAF et al., 2014; EL ATFY et al., 2023). *Elaterocolpites castelainii*, another elaterate, first appeared in the late Albian (HOCHULI, 1981). Although E. *klaszii* and *E. castelainii* also have their widest distribution in the Late Albian and Early Cenomanian of Egypt and Africa, they were considered to be restricted to the Upper Albian in the Lower Benue Trough of Nigeria (JARDINÉ, 1967). Usually, gymnosperms such as

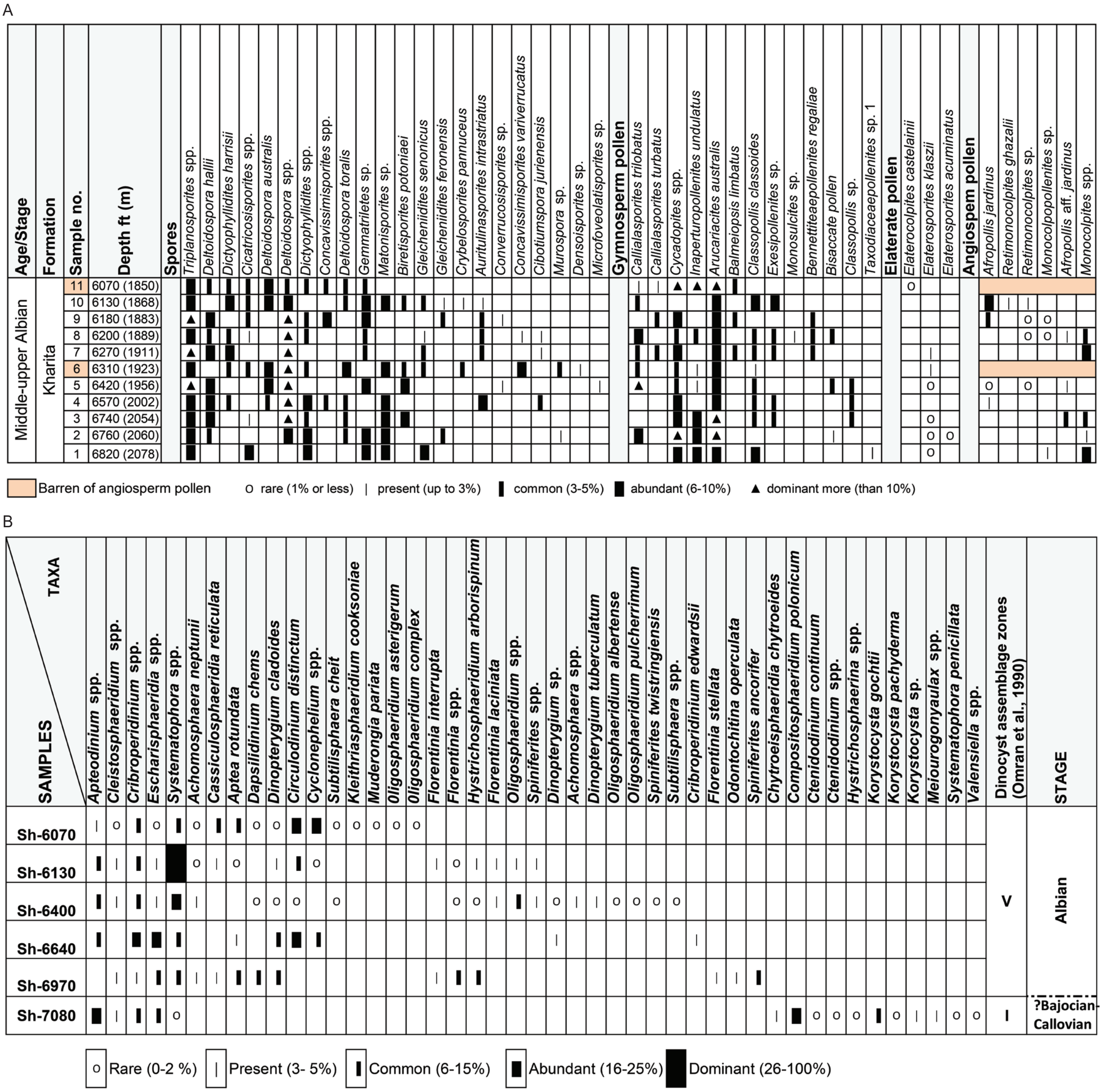

Figure 5. A) Semi-quantitative distribution, by highest occurrence, of terrestrial spores and pollen, (calculated from total sporomorphs) in the investigated Albian interval, Sharib-1X borehole; **B)** Dinocysts semi-quantitative distribution chart by highest occurrence, Sharib-1X borehole (redrawn after Mahmoud, 1989; taxonomic names revised according to FENSOME et al., 2019).

Araucariacites disappear in African basins during the Cenomanian (JARDINÉ & MAGLOIRE, 1965). *Retimonocolpites ghazalii* may be an important angiosperm pollen in the borehole; although the uppermost sample 11 has rare findings, its highest occurrence levels in the lower Albian in the Shushan Basin (MAHMOUD et al., 2023) supports an Albian date. The diverse dinoflagellate cyst association recovered by the second author (MAHMOUD, 1989), with no diagnostic Jurassic dinocysts (Fig. 5B), see next paragraph, confirms our Cretaceous (Albian) dating. The spores and gymnosperm associations, on the other hand, recovered here are long-ranging, although they are of Cretaceous aspect. However, *Murospora* is a significant Aptian/Albian spore in the regional palynofloras of Egypt. *Crybelosporites pannuceus* enters the palynological records during the Aptian in Sudan (KASKA, 1989). It appeared later (Albian) in Africa (NE Nigeria – LAWAL & MOULLADE, 1986; NE Libya – BATTEN & UWINS, 1985), in South America (Peru – BRENNER, 1968) and in the Middle East (Qatar – EL BEIALY & AL-HITMI, 1994). Younger Albian–Cenomanian records were also recorded in Egypt (SCHRANK & MAHMOUD, 1998). Several palynological contributions from the Western Desert of Egypt considered *Concavissimisporites punctatus* to date the early-middle Albian palynofloral assemblages (e.g., EL SHAMMA et al., 1999; TAHOUN et al., 2015; ABOUL ELA et al., 2020) and to discriminate between the Kharita and the overlying Bahariya Formations (ABOUL ELA et al., 2020). In Europe, this species defines the middle Albian deposits in Portugal

(HASENBOEHLER, 1981). Some grains within *Concavissimisporites* spp. in the uppermost samples (9 and 11) bear affinities with *C. punctatus* that can also support an Albian date.

OMRAN et al. (1990) studied the interval 2124 to 1850 m and assigned it to the middle-late Albian based on dinoflagellate cysts (*Dinopterygium cladoides, Oodnadattia tuberculata* and *Subtilisphaera cheit*). They also addressed the absence of the Cenomanian palynoflora and any other diagnostic sporomorphs, except for a few discoveries of the two genera *Clavatipollenites* and *Elaterosporites* to support their suggestion. OMRAN et al. (1990) did not provide any quantitative or qualitative data about the five samples studied from Sharib-1X, except for the composite chart of the three wells they studied in their published paper. They only illustrated the main palynofloral group where there is a high percentage of marine palynomorphs. They assigned the studied interval to Palynoflora D3 (Albian/?Early Cenomanian), which is characterized by the presence of *Achomosphaera*, *Cassiculosphaeridia reticulata*, *Cyclonephelium*, *Dapsilidinium chems*, *Dinopterygium cladoides*, *Escharisphaeridia*, *Florentinia mantellii*, *Florentinia stallata, Hystrichosphaeridium arborispinum* and *Odontochitina costata*. The palynoflora is dominated by *Cribroperidinium* and *Systematophora*. Jurassic marker dinocysts are completely missing in the studied interval of the well, except in the lowermost sample, at a depth of 2124 m, where *Korystocysta kettonensis* (now *K. gochtii*) and *Korystocysta norrisii* (now *K. pachyderma*) have their first downhole occurrence in this sample, with an unequivocal Jurassic (?Bajocian–Callovian) age. As has been noted earlier in the "results" section, details of these dinocysts, beside others, are presented for the investigated Sharib-1X well. This semi-quantitative distribution is more robust than that of the terrestrial palynomorphs, especially the angiosperms and the elaterates, and reflects appreciable percentage frequencies of index Cretaceous and other dinoflagellates. However, OMRAN et al. (1990) did not provide any data about the lithostratigraphic unit they studied from Sharib-1X (no formation name is mentioned) while WEPCO (1971) assigned the studied interval to the Masajid Formation (Jurassic). The Kharita Formation is primarily a clastic unit, and there is no published data indicating such thick carbonate bodies or shale intercalations within the formation. However, on the basis of the current findings, the carbonate interval is not as thick as the Masajid Formation (Jurassic) and correlates with the Kharita Formation (Cretaceous), but the uppermost carbonates can be correlated with the basal Medewar Formation (lateral equivalent of the Bahariya Formation), as can be seen from a generalized stratigraphic column of the Western Desert (SCHLUMBERGER, 1984, 1995; column presented in LOTFY et al., 2020, fig. 2, p. 245). A few metres above these samples in the same Sharib-1X borehole, few dinoflagellates of *Adnatosphaeridium caulleryi, Ctenidodinium combazii, Escharisphaeridia pocockii, Sentusidinium rioultii* and *Systematophora penicillata*, were recorded from the carbonate interval by ZOBAA et al. (2013), and discussions therein, Palynozone 1, depths from 1880 to 1818 m; dated as Jurassic. For example, *A. caulleryi* has biostratigraphic records of Berriasian–Valanginian (MILLIOUD et al., 1975), Berriasian–lower Hauterivian (SMELROR et al., 1991) and Valanginian–lower Aptian (VAVRDOVÁ, 1964). Also, *S. penicillata* was discovered in the local record in the lower Hauterivian (e.g., IBRAHIM & SCHRANK, 1996). These dinocysts normally occur in the Jurassic but Cretaceous records were also known. ZOBAA et al. (2013) suggested a Middle to Late Jurassic age based on the presence of *C. combazii* (not illustrated by photomicrographs) being no younger than the Callovian. They noted the absence of any angiosperm pollen in this interval. The presumed oxidation in the carbonate body do not contrast the palynomorph occurrences observed by ZOBAA et al. (2013), except that some palynomorphs might have expected to be oxidized and/or degraded. On the basis of the discussions in the above paragraphs, the present miospores of the Kharita Formation can be correlated to a middle-late Albian age.

6.2. Palaeoenvironmental inferences

The relative percentages of palynomorphs and palynofacies categories of the Kharita Formation, as plotted on SMP and APP ternary plots (Figs. 6A, B), suggest an oxic, to dysoxic–suboxic, deltaic environment for deposition, near fluvial sources (TYSON, 1995). The low abundance of AOM in most samples may suggest shallow shelf sedimentation and dysoxic–suboxic conditions (e.g., DOW & PEARSON, 1975; BUJAK et al., 1977; TYSON, 1995; ALAUG et al., 2014). In this study,

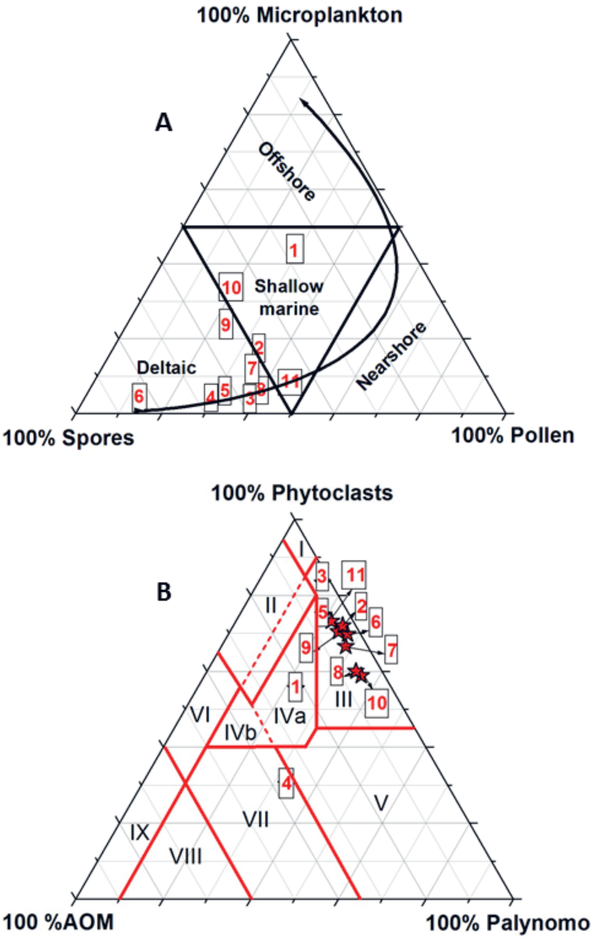

Figure 6. A) SMP (spores, pollen, microplankton) ternary diagram (after FEDEROVA, 1977; DURINGER & DOUBINGER, 1985; TYSON, 1995; TRAVERSE, 2007); **B)** APP (AOM/palynomorphs/phytoclasts) ternary diagram of the total palynological organic matter (TPOM) in the study borehole, with the Roman numbers indicating the fields explained by TYSON (1995, p. 446, 447). Red stars refer to the present eleven investigated samples.

AOM is regarded as including all particulate structureless components at the scale of light microscopy that could represent a diverse array of marine or non-marine origins. In marine sediments, AOM is mainly derived from phytoplankton and bacteria (see TYSON, 1995). The term "amorphous" is used by palynologists in a descriptive sense, regardless of origin and derivation. The low abundance and low diversity of dinoflagellate cysts confirm deposition in very shallow marine, to coastal, settings (e.g., TYSON, 1993). The redox states seem to have influenced the dinoflagellates association in the formation, as seen from their lower diversities as recorded by OMRAN et al. (1990). Sensitive, heterotrophic species of dinoflagellates may undergo degradation due to excess oxygen in the depositional basin. Such heterotrophic cysts live in areas influenced by freshwater influx with rich nutrients (ZONNEVELD et al., 2007, 2009). Higher amounts of AOM at two horizons, as seen from samples 1 and 4 (depths 2078 m and 2002 m), are typical of sediments deposited in anoxic marine settings (SUMMERHAYES, 1987; TYSON, 1987). The temporal change in the m/c ratio is useful in identifying a proximal-distal trend in sedimentation (e.g., PITTET & GORIN, 1997). Accordingly, the observed low m/c values, across most of the investigated borehole section, confirm marginal (proximal) settings. Exceptionally, at the basal and upper parts of the Kharita Formation, where the m/c ratio increases, more open marine settings may have occurred, as this ratio is relatively affected by taphonomic processes, especially biodegradation (BOMBARDIERE & GORIN, 2000), besides the borehole's setting (see geological setting section). During the Albian–Cenomanian era, Egypt's northern basins featured fluvio-deltaic to shallow marine habitats. The Kharita Formation's sedimentary successions were mostly made up of mixed siliciclastic and minor carbonate rocks. This caused difficult conditions for various calcareous nannofossils and foraminiferal assemblages (MANSOUR et al., 2022). Also, because of the nature of the cutting rock samples used in this study, it is often difficult to ensure that a given species' first appearance datum (FAD) and last appearance datum (LAD) correspond to its true inception and extinction due to taphonomic biases and/or lithologic facies control. As a result, the recorded real lowest occurrence (LO) and highest occurrence (HO) values are utilized here rather than the first and last appearances. To prevent caving, the palynomorph zones are usually delineated using the highest occurrence (HO) data of the marker types. However, tested lowest occurrence (LO) data are occasionally employed in the absence of HO of marker taxa (Fig. 5A) (MAHMOUD et al., 2019).

6.3. Degradation in the top Kharita Formation

Post-depositional bio-oxidation of wood phytoclasts in coastal sediments with varying water tables was previously documented by POCOCK (1982). In addition, preservation in sand-rich sediments might explain the increase in blackwood and the subsequent decline in the brown-to-black wood ratio that drops out offshore (GÖTZ et al., 2005, 2008; HABIB, 1982; SUMMERHAYES, 1987; TYSON, 1989). ZOBAA et al. (2013, p. 60, fig. 7) described highly mature to overmature gas-prone/inert materials in most of the interval, manifested by the dominance of opaques, associated with medium to dark brown palynomorphs and a low AOM content. They attributed this palynofacies, in relatively coarse-grained, high energy organic-poor facies, to a shallow marine, slightly oxic to suboxic, environment. We believe that these characteristics are suggestive of pronounced oxidation, which may have led to a partial degradation of the accumulated organic matter. In this work, we re-investigated two samples (nos. 10 and 11, at depths of 1868 m to 1850 m), that are located within this opaque-dominated interval (Fig. 7). Sample no. 10, only a few metres

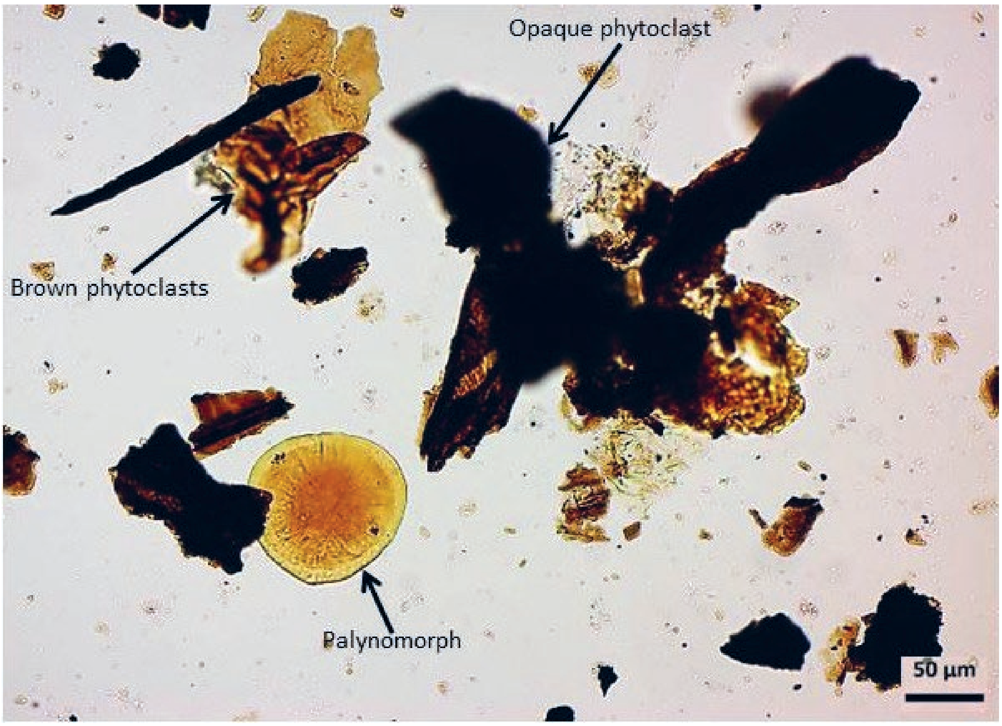

Figure 7. Photomicrograph showing the main constituents of the recorded palynofacies in the investigated samples.

above the sample that contains their lowest opaques at 1871 m, yielded frequent records of *Afropollis* and other angiosperms. In contrast, sample 11 lacks pollen, although it also has a relatively very low opaque content. We attributed that to the impact of the environmental restriction (i.e., marginal setting) rather than being due to oxidation of the organic matter, particularly in such a carbonate environment where flowering plants are likely to be scarce or absent. Note that the m/c ratio declines to a minimum in this sample. Angiosperms increase in frequency in association with the increase in the m/c ratio, namely away from the impact of the environmental restriction. Based on the foregoing discussion, the relatively lower percentages of opaques (see Fig. 7) might reflect a low to moderate oxidation impact. Consequently, most of the palynomorph association can be preserved. However, biodegradation, due to the destructive activity of bacteria and fungi in the fossil pollen grains and spores is common, (e.g., TIWARI & SINGH, 1986) and cannot be attributed to oxidation or other physicochemical processes (ELSIK, 1966).

The general, shallow marine, nature of the Kharita Formation may explain the recorded low-diversity angiosperm association in the investigated non-oxidized interval of the Sharib-1X borehole. The location of the borehole, at the northern edge of the east-west trending Sharib-Sheiba high regional uplift, implies deposition of the sediments at such shallower settings. This local regressive episode coincides with the late Aptian–Albian regional uplift, which affected the majority of northern Egypt (MESHREF, 1990). Degradation of palynomorphs in the investigated residues is not expected since the present processing technique completely avoided using oxidizing agents, the excessive use of which may lead to degradation (SCHRANK, 1988).

6.4. Palaeogeographic significance of the Kharita miospores

The presence of elaterates, along with other miospores, reflects the affinity of the Sharib-1X palynoflora with the Albian–Cenomanian African–South America (ASA) palynofloral province, first introduced by HERNGREEN (1974) and subsequently recognized in South American and African countries, the Middle East, Bahamas Islands, Southern Alps, westernmost China and Papua-New Guinea (HERNGREEN & JIMENEZ, 1990; DINO et al., 1999). This province was previously inferred and discussed in Egyptian literature (e.g., DEAF et al., 2014). Our data clearly reflect the influence of the break-up of the continents of Africa and South America and the gradual opening of the Atlantic Ocean in the late Aptian to early Albian, and the resultant global palaeoclimate change near the equator (Fig. 8) from the earlier relative drought to humid conditions. These conditions were recently documented from the Doseo Basin, Central African Rift system (DOU et al., 2024), where gymnosperms (*Araucariacites* and *Cycadopites* here) and fern spores (*Deltoidospora* and *Triplanosporites* here) account for a high proportions, with a small amount of angiosperms.

7. CONCLUSIONS

Terrestrial Albian sporomorphs, dominated by pteridophytes and gymnosperms, were recorded from the Sharib-1X borehole. The *Afropollis jardinus* pollen and the elaterates (*Elaterocolpites castelainii, Elaterosporites klaszii*) confirm an Albian age of the investigated interval of the Kharita Formation. Miospores therefore can be a powerful tool in the biostratigraphy of sequences that were deposited in regressive shallow marine conditions (the case herein), resulting in a paucity of dinocyst assemblages and other microplankton. Age assessments based on palynomorphs, especially at the Jurassic/Cretaceous transition, require a comprehensive synopsis of the ranges of the recorded species. Looking at the whole palynofacies is necessary to infer the degradation of palynomorphs. Care should be considered when applying terrestrial pollen and spores in biostratigraphy if the palynoflora shows evidence of oxidation, environmental restriction or biodegradation effects. These factors may result in incomplete palynofloras being recorded, as discovered in

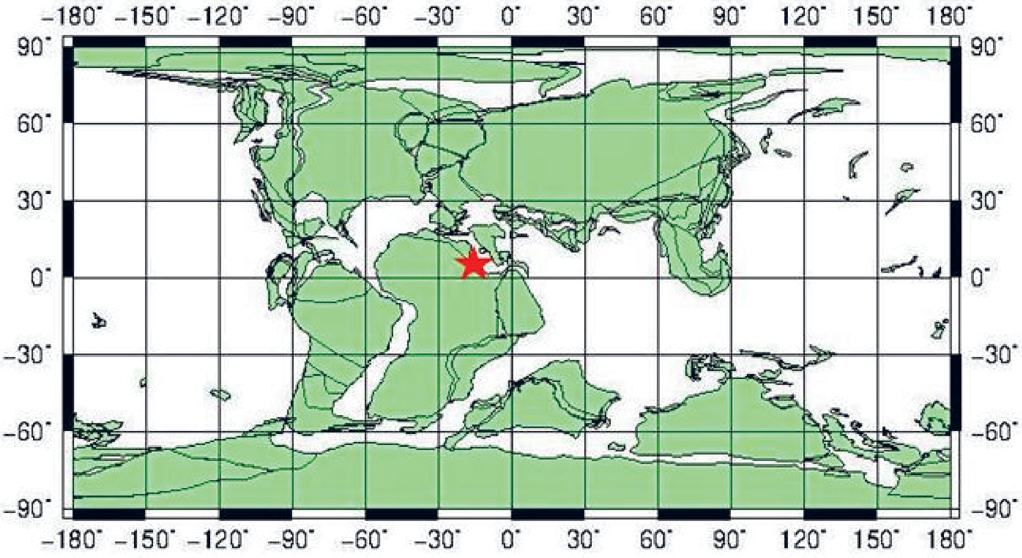

Figure 8. Palaeogeographic map for the beginning of the Albian stage, 113 Ma (after HAY et al., 1999; the plate tectonic maps are composed from the data files used for the publication), indicating approximate position of Egypt (red star). Ages are taken after the latest issue of the "International Chronostratigraphic Chart" (COHEN et al., 2013; updated).

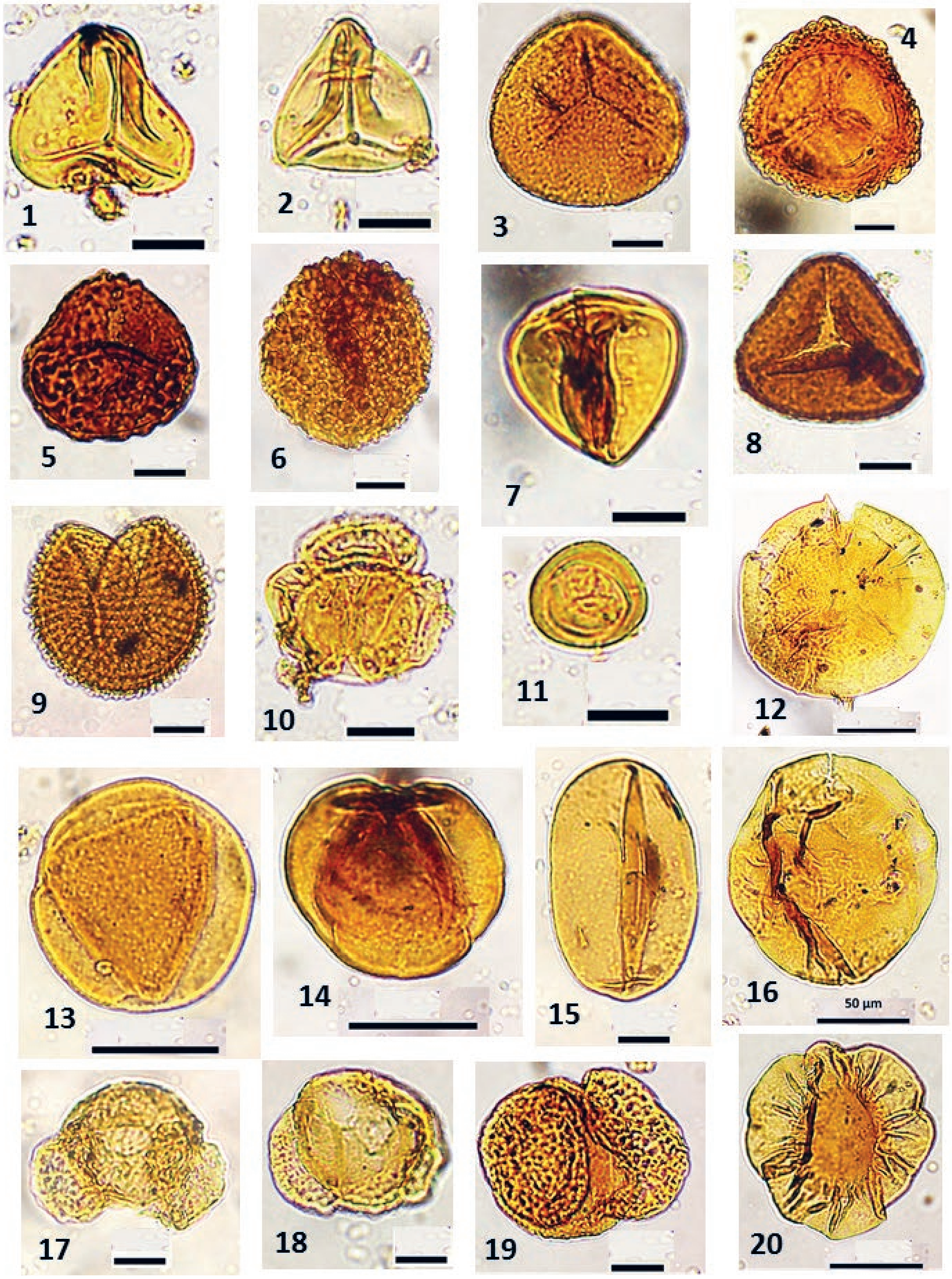

Figure 9. Scale bar = 20 µm, except 12, 13, 14, 16 and 20 scale bar =50 µm. **1** – *Dictyophyllidites harrisii* COUPER, 1958, depth: 2002 m, A, no.: 4, indices: 10.5/83.6. **2** – *Deltoidospora hallii* MINER, 1935, depth: 2002 m, A, no.: 4, indices: 7.6/92.3. **3** – *Microfoveolatisporites* sp., depth: 1956 m, C, no.: 5, indices: 14.5/95.5. **4** – *Densoisporites* sp., depth: 1923 m, A, no.: 6, indices: 11.5/87. **5** – *Converrucosisporites* sp., depth: 1883 m, A, no.: 9, indices: 12/95. **6** – *Verrucosisporites* sp., depth: 1956 m, A, no.: 5, indices: 6/93. **7** – *Triplanosporites* sp., depth: 1868 m, A, no.: 10, indices: 23/102. **8** – *Converrucosisporites* sp., depth: 1956 m, B, no.: 5, indices: 22.3/105. **9** – *Prasinophycean phycomata*, depth: 2078 m, A, no.: 1, indices: 22/107.5. **10** – Tetrad pollen depth: 2002 m, A, no.: 4, indices: 10.5/81.6. **11** – *Classopollis* sp., depth: 2002 m, A, no.: 4, indices: 6.4/94. **12** – *Callialasporites* sp., depth: 1850 m, B, no.: 11, indices: 12/85. **13** – *Callialasporites* sp. cf. *C. trilobatus* (BALME, 1957) SUKH DEV, 1961, depth: 1889 m, B, no.: 8, indices: 10.5/97.8. **14** – *Callialasporites trilobatus* (BALME) SUKH DEV, 1961, depth: 1868 m, A, no.: 10, indices: 15/105.5. **15** – *Monosulcites* sp., depth: 1889 m, B, no.: 8, indices: 13.5/91.8. **16** – *?Callialasporites* sp., depth: 2060 m, B, no.: 2, indices: 9.3/90. **17, 18, 19** – Bisaccate pollen, depth: 1889 m, A, no.: 8, indices: 11.7/90.5; depth: 2060 m, A, no.: 2, indices: 11.6/91.8; depth: 1956 m, B, no.: 5, indices: 12/99.7. **20** – *Callialasporites dampieri* (BALME, 1957) SUKH DEV, 1961, depth: 2060 m, A, no.: 2, indices: 11.4/84.

the carbonate interval, at the top of the Kharita Formation in the investigated borehole. This can manifest by the rarity of certain palynomorphs, probably the angiosperms, the paucity of AOM, the occurrence of extraordinarily abundant opaques, and the low palynomorph diversities. These carbonates are not widespread in the regional record, only occur as thin beds; and their thickness in this borehole (~30 m thick) needs further investigation. However, the Jurassic carbonates of the Masajid Formation are much thicker and measure a few hundreds of metres. In general, the subsurface stratigraphic column of the northern Western Desert of Egypt shows thick carbonates of the Medewar Formation (lateral equivalent of Bahariya

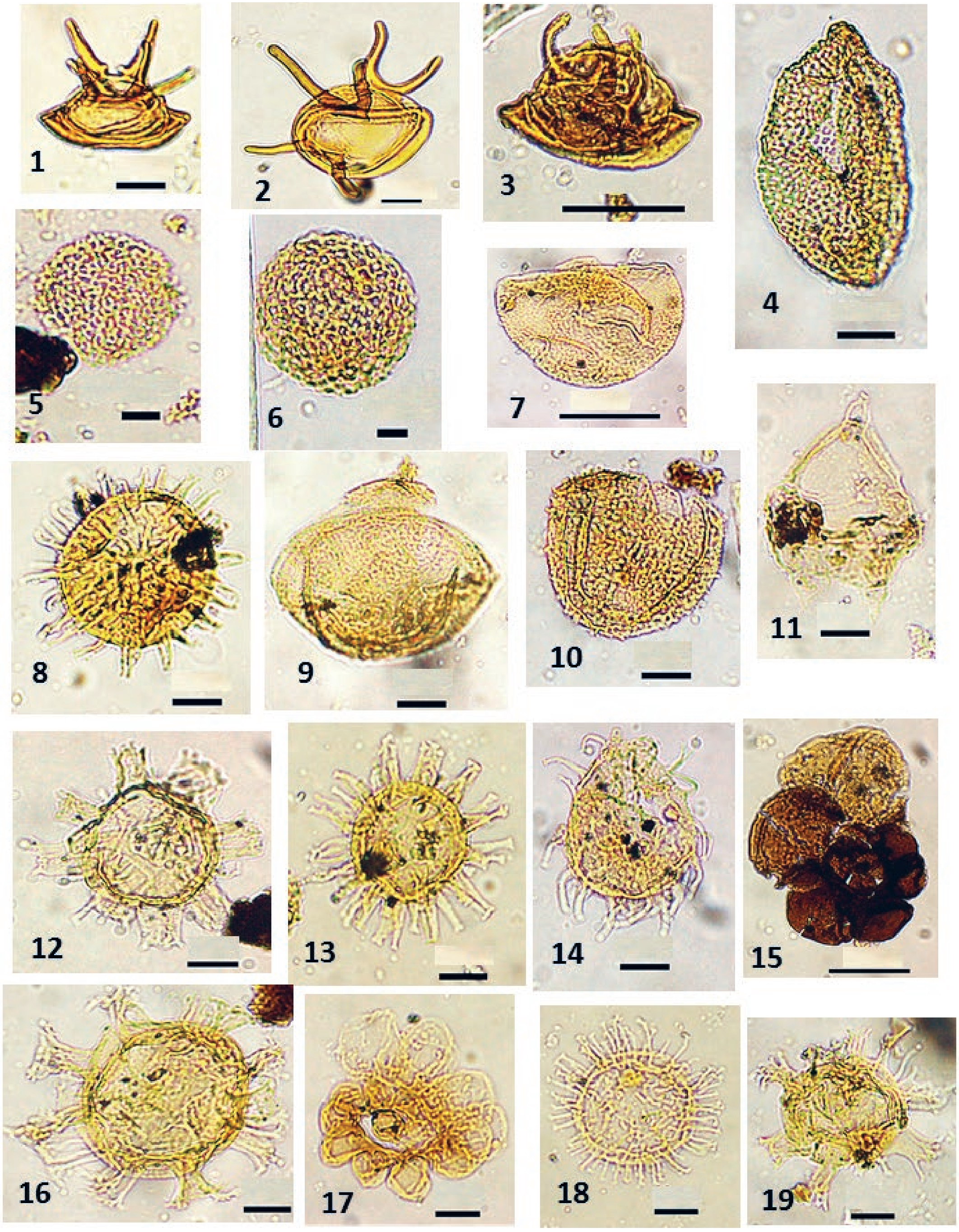

Figure 10. Scale bar = 20 µm, except 5 and 6 scale bar = 10 µm and 3, 7 and 15 scale bar =50 µm. **1, 2, 3** – *Elaterosporites klaszii* (JARDINÉ & MAGLOIRE) JARDINÉ, 1967, depth: 1923 m, B, no.: 6, indices: 7.7/91.7; depth: 1911 m, A, no.: 7, indices: 9.1/102.5; depth: 2060 m, B, no.: 2, indices: 9/90.8. **4** – *Retimonocolpites ghazalii* IBRAHIM, 2002a, depth: 1868 m, C, no.: 10, indices: 14.5/86.5. **5** – *Afropollis jardinus* DOYLE et al., 1982, depth: 2002 m, A, no.: 4, indices: 12.5/93.7. **6** – *Afropollis* aff. *Jardinus* DOYLE et al., 1982, depth: 1956 m, B, no.: 5, indices: 12.7/85.6. **7** – *Escharisphaeridia* sp., depth: 1868 m, B, no.: 10, indices: 9.6/95.5. **8, 14** – *Cleistosphaeridium* spp., depth: 2078 m, A, no.: 1, indices: 16.4/107; depth: 1883 m, A, no.: 9, indices: 18.2/86.5. **9** – ?*Kallosphaeridium* sp. (note the A attached – like archeopyle), depth: 1889 m, A, no.: 8, indices: 17/99.5. **10** – *Meiourogonyaulax* sp., depth: 1889 m, A, no.: 8, indices: 19/111.6. **11** – *Subtilisphaera* sp., depth: 1923 m, A, no.: 6, indices: 19.4/105.7. **12** – *Florentina mantellii* (Davey & Williams) Davey & Verdier, 1973, depth: 2060 m, B, no.: 2, indices: 9/91.2. **13** – Indet. dinoflagellate cyst, depth: 2078 m, A, no.: 2, indices: 12/86.7. **15, 17** – Microforaminiferal linings, depth: 2078 m, A, no.: 1, indices: 12.7/108.8; depth: 2078 m, A, no.: 1, indices: 11.5/97.8. **16** – ?*Systematophora* sp., depth: 1923 m, B, no.: 6, indices: 14/106.5. **18** – cf. *Operculodinium* sp. depth: 2078 m, A, no.: 1, indices: 7/98. **19** – *Florentinia* sp., depth: 1889 m, B, no.:8, indices: 13.4/112.

Formation) just above the Kharita Formation. The overall recorded palynomorphs reveal that the Kharita Formation is deposited in a marginal, oxic to dysoxic–suboxic, environment. It may have shifted to distal settings, at the base and top of the Kharita Formation, where the marine elements and AOM increase in abundance. At these levels, greater counts of the angiosperm were seen. This may confirm that the preservation of these angiosperms may have affected by the (restricted) environment. The Kharita palynofloras bear great affinity to ASA palynofloristic province and reflect the influence of the break-up of the continents of Africa and South America and the gradual opening of the Atlantic Ocean in the late Aptian to early Albian, and the resultant global palaeoclimate change near the equator to humid conditions.

ACKNOWLEDGEMENT

Thanks are due to the Egyptian General Petroleum Corporation (E.G.P.C.) for providing the material and borehole log for the present work. We appreciate the suggestions of two anonymous reviewers for their informative and helpful remarks. The authors would like to thank Tea FLUKSI (Managing Editor, Geologia Croatica) for her assistance and remarks kindely offered during the publication procedures.

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