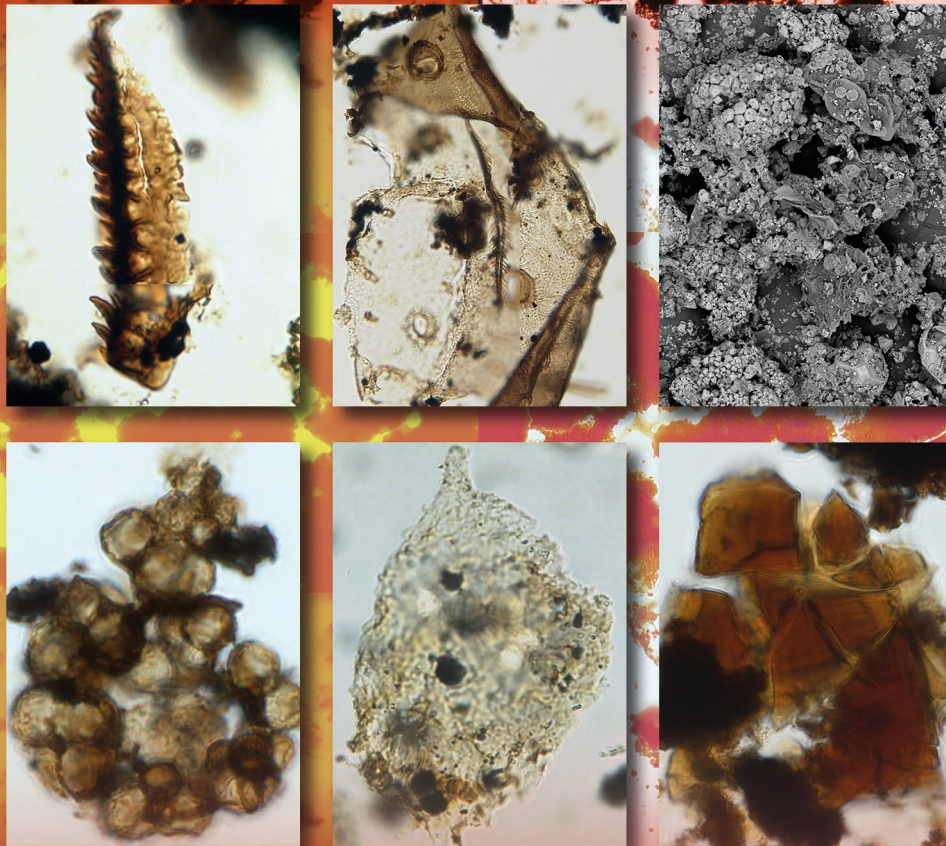


Non-pollen palynomorph and palynofacies assemblages from the Lower Cretaceous of Iraq: A glimpse into palaeobiology and palaeoenvironment

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ABSTRACT

The Lower Cretaceous Yamama Formation is well-known as one of the main carbonate oil reservoirs for many of the southern Iraq oilfields. However, its depositional environment has so far been poorly described using palynological techniques. Palynological assemblages from the Lower Cretaceous Yamama Formation in southern Iraq contain variable proportions of non-pollen palynomorphs (NPPs). Although this is the first record of such assemblages from the Cretaceous of Iraq, they appear very diverse and comprise microforaminiferal linings, arthropod cuticles, *Botryococcus* Kützing, 1849, dinoflagellate cysts, fungal remains, *Leiosphaeridia* Eisenack, 1958, and *Palambages* Wetzel, 1961. Palynofacies analyses reveal that samples are generally dominated by AOM and most of them contain smaller quantities of translucent phytoclasts and charcoal. These records, in addition to previous studies, suggest that deposition of the studied strata of the Yamama Formation took place under anoxic conditions in the inner to outer neritic zone in a relatively near-shore setting, as shown by significant terrestrial input.

KEY WORDS

Leiosphaeridia,
Botryococcus,
Palambages,
dinoflagellates,
Yamama Formation,
Cretaceous,
Iraq,
non-pollen
palynomorphs,
microforaminiferal
linings.

RÉSUMÉ

Assemblages de palynomorphes et de palynofaciès non polliniques du Crétacé inférieur d'Irak : aperçu de la paléobiologie et du paléoenvironnement.

La formation Yamama du Crétacé inférieur, dans le sud de l'Irak, est bien connue pour être l'un des principaux réservoirs carbonatés de pétrole pour de nombreux champs pétrolifères dans ce secteur. Toutefois, son environnement de dépôt a jusqu'à présent été peu décrit à l'aide de techniques palynologiques. Les assemblages palynologiques de la formation de Yamama contiennent des proportions variables de palynomorphes non polliniques (NPP). Bien qu'il s'agisse de la première observation de ce type d'assemblages dans le Crétacé irakien, ils semblent très diversifiés et comprennent des revêtements de microforaminifères, des cuticules d'arthropodes, des *Botryococcus* Kützing, 1849, des kystes de dinoflagellés, des restes de champignons, des *Leiosphaeridia* Eisenack, 1958 et des *Palambages* Wetzel, 1961. Les analyses des palynofaciès révèlent que les échantillons sont généralement dominés par des AOM et que la plupart d'entre eux contiennent de plus petites quantités de phytoclastes translucides et de charbon de bois. Ces enregistrements, qui s'ajoutent aux études précédentes, suggèrent que le dépôt des strates étudiées de la formation de Yamama a eu lieu dans des conditions anoxiques dans la zone néritique interne à externe, dans un environnement relativement proche du rivage, comme le montre l'importance des apports terrestres.

MOTS CLÉS

Leiosphaeridia,
Botryococcus,
Palambages,
dinoflagellés,
Formation de Yamama,
Irak,
Crétacé,
palynomorphes non
polliniques,
doublures
microforaminifères.

INTRODUCTION

Non-pollen palynomorphs (NPPs) comprise organic-walled microfossils that are commonly preserved in palynological preparations; similar to pollen and spores, they are more resistant to acid digestion, and as such, they survive palynological maceration using demineralization acid treatments. Marine NPPs range from the well-known dinoflagellates to less well-studied groups, like foraminiferal and ostracod linings, tintinnids, organic-walled ciliates, copepod, trematode, and worm remains (Mudie *et al.* 2021a). They provide an alternative source of information when pollen and spores are scarce in sediments (Limaye *et al.* 2007; Mudie *et al.* 2021b). In recent years, detailed investigations demonstrating the value of NPPs, particularly for the Quaternary, have extended nearly worldwide (e.g. Cook *et al.* 2011; Shumilovskikh & van Geel 2020; Mudie *et al.* 2021a; Shumilovskikh *et al.* 2021 and references therein). Furthermore, a detailed investigation of NPPs (preferably in combination with pollen and other data) allows a better understanding of palaeoecological conditions and changes that can help to assess the relative importance of climate change during the spatial-temporal framework of deposition (Gelorini *et al.* 2012; Boyd *et al.* 2018; Houben *et al.* 2019; among others).

The Lower Cretaceous Yamama Formation is one of the main carbonate reservoirs as well as good source rocks in southern Iraq and is equivalent to the Minagish Formation in Kuwait (Aqrabi *et al.* 2010; Al-Khafaji *et al.* 2022). Its facies change both laterally and vertically and it, therefore, acts as a source rock in some locations in southern Iraq, but not in others (Abeed *et al.* 2011; Al-Jawad & Saleh 2020). This study is based on the palynological examination of five subsurface core samples (Table 1) from the Yamama Formation from boreholes R-167, Ru-158, Su-08, and Zb-42 in southern Iraq (Fig. 1). The current study aims to identify and document the NPPs types and provide first insights into their qualitative and quantitative variations. In addition, it also

aimed to introduce more information on how to interpret the palynofacies content, which is useful for palaeoenvironmental and palaeoecological interpretation (e.g. Batten 1996; El Atfy 2021).

GEOLOGIC SETTING AND LITHOSTRATIGRAPHY

The Mesopotamian Basin locates in the east of the Stable Shelf (Aqrabi *et al.* 2010) and encompasses most of central, southern, and western Iraq. It was subdivided by Buday & Jassim (1984) into 3 subzones, namely from north to south: Tigris, Euphrates, and Zubair, where the studied cores were retrieved (Fig. 1). The study area as a part of the Zubair subzone is located in the south of Iraq in the vicinity of the city of Basra and characterized by a semi-flat surface with buried whaleback-shaped anticlines that formed the traps for the majority of the oil discovered in southern Iraq (Abeed *et al.* 2013).

The Middle Jurassic-Lower Cretaceous sequences of the southern Mesopotamian Basin in Iraq comprise mostly carbonate and evaporite rock units. They were primarily deposited during a period of isolation of the main intra-shelf basin of the Mesopotamian Basin from the Neo-Tethyan Ocean due to renewed rifting. Deposition within the basin occurred in a restricted, relatively deep-water environment during the Middle Jurassic, after which deposition became more evaporitic from the late Kimmeridgian to the early Tithonian (Jassim & Buday 2006a, b). During the Tithonian, a period of complete isolation from the Neo-Tethys was achieved, marked by the lowstand evaporite deposits of the Gotnia Formation. Active tectonism continued during the late Tithonian to the Valanginian in the study area, causing a sudden cessation of evaporite deposition, and the commencement of a new depositional cycle that consisted of condensed deep basinal organic-rich mudstones, marls, and micritic-oolitic limestones (Aqrabi *et al.* 2010).

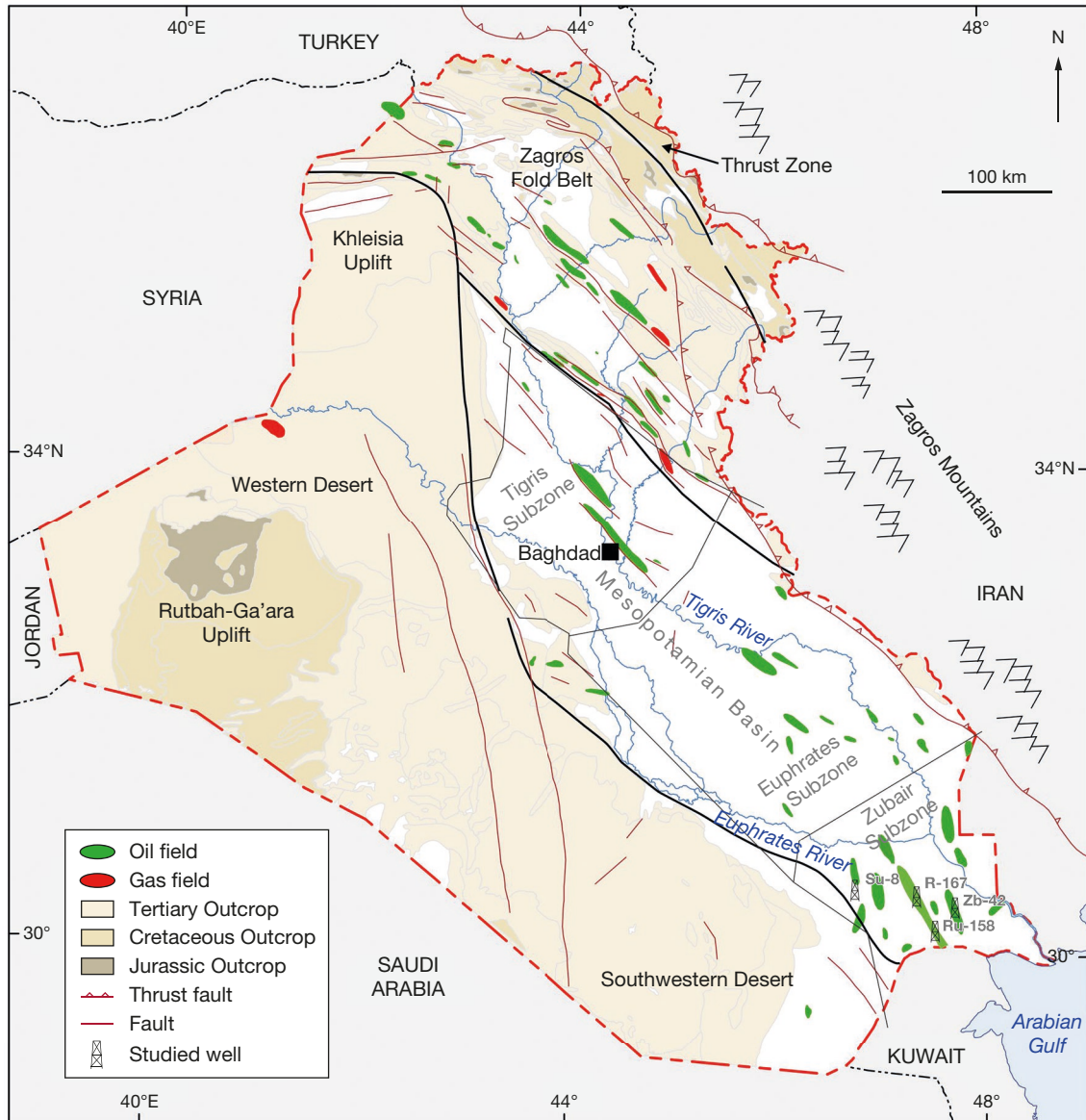


FIG. 1. — Tectonic map of Iraq showing hydrocarbon accumulations in Mesopotamian Basin and Zagros fold belt, and the approximate locations of the studied wells in southern Iraq. Abbreviations: **R**, Rumaila North; **Ru**, Rumaila South; **Zb**, Zubair; **Su**, Subba. Modified after Pitman *et al.* (2004) and Abeed *et al.* (2013).

The Yamama Formation (Berriasian-Valanginian) represents a regressive cycle deposited on a shallow carbonate ramp that was under clastic influence from the nearby land (Al-Khafaji *et al.* 2022). This depositional setting represents a key factor in interpreting the organic matter content. Its thickness varies between 200-300 m in the study area, with lithofacies largely shaped by tectonism and consisting of brown detrital limestone within thin shale beds, covered by micritic and oolitic limestone (Sadooni 1993; Jassim & Buday 2006b). The Yamama Formation is conformably underlain by the Sulaiy Formation, and grades upward into the Ratawi Formation, which is a mixed suite of limestone, shale, siltstone, and sandstone (Saleh 2014). It is evident that the Yamama Formation is acting as a series of source-reservoir units in the petroleum system of southern Iraq, indeed, it forms a series of highly productive carbonate reservoirs in many of the super-giant

oil fields in southern Iraq (e.g. Sadooni 1993; Aqrabi *et al.* 2010; Abeed *et al.* 2011; Al-Jawad & Saleh 2020).

MATERIAL AND METHODS

The current study is based on core samples of carbonates from the Lower Cretaceous Yamama Formation (Abeed *et al.* 2011; El Atfy *et al.* 2016). They were chosen due to their high-organic content as well as their challenging palynological yield, which is full of NPPs. For this study, 15-20 g of each sample was prepared for palynological examination using demineralization extraction methods using HCl-HF treatment (e.g. Wood *et al.* 1996). Subsequently, the residues were sieved employing 10 µm nylon mesh. No oxidative processes were run. Later, residues were transferred from distilled

TABLE 1. — Percentages for the recorded NPPs and palynofacies particles as well as TOC (wt.%) results of the studied samples (based on data from Abeed *et al.* 2011).

| Sample | Well | Depth (m) | AOM% | Microforaminiferal linings% | Phytoclasts% | Dinoflagellates% | Charcoal% | Leiosphaeridia% | Botryococcus% | Palambages% | Arthropods% | Fungi% | TOC (wt.%) |
|--------|--------|-----------|------|-----------------------------|--------------|------------------|-----------|-----------------|---------------|-------------|-------------|--------|------------|
| 09-234 | Ru-167 | 4141.0 | 50 | 30 | 5 | 5 | 3 | 3 | 1 | 2 | 1 | 0 | 0.32 |
| 09-242 | Ru-158 | 3901.0 | 64 | 20 | 4 | 0 | 5 | 0 | 0 | 2 | 1 | 4 | 0.10 |
| 09-243 | Su-08 | 3568.6 | 95 | 5 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0.26 |
| 09-255 | Su-08 | 3571.9 | 54 | 25 | 7 | 0 | 7 | 5 | 0 | 2 | 0 | 0 | 2.72 |
| 09-262 | Zb-42 | 3780.0 | 24 | 30 | 10 | 6 | 1 | 7 | 2 | 10 | 5 | 5 | 0.24 |

water onto coverslips which were dried at 30-40 °C. The coverslips were affixed onto slides with a droplet of Elvacite® 2044 (Lucite International; Tennanats GmbH) dissolved in xylene. Two to three slides of each sample were routinely observed with transmitted- and incident-light fluorescence microscopy. Photomicrographs were taken in transmitted white and blue light using an Axiocam 512 color digital camera attached to a Zeiss Axio Imager. M2 microscope. Approximately 200 particles, were counted using transmitted light microscopy with a magnification of 200 × and 400 ×. Additionally, drops of the residue concentrate were dried and mounted on Scanning Electron Microscope (SEM) stubs. Subsequently, all the stubs were sputter-coated with gold-platinum. SEM photos were taken using a JEOL JSM 6490 LV scanning electron microscope (accelerator current 20 kV) at the Department of Geosciences, University of Tübingen. An England Finder reference accompanies the sample number for each illustrated specimen. All microscope slides, SEM stubs, and palynology residues are stored in the Geology Department, Mansoura University, Egypt.

RESULTS AND DISCUSSION

The studied samples, representing small-scale windows into the Yamama Formation in boreholes R-167 (4141 m), Su-8 (3568.6 and 3571.9 m), Zb-42 (3780 m) and Ru-158 (3901 m), did not yield significant pollen and spore assemblages (Table 1). Amorphous organic matter (AOM) was generally the most dominant element of the palynofacies, although samples 09-234, 09-262, and 09-255 are dominated by microforaminiferal linings. A similar palynofacies content has been recently recovered from the Yamama Formation in the Mesopotamian Basin, Iraq, in which AOM reaches up to 100% (Al-Khafaji *et al.* 2022). The remainder of the NPP assemblages contained algae, fungal spores, dinoflagellates, *Palambages* Wetzel, 1961, scolecodonts, and arthropod cuticles (Fig. 2). Scolecodonts (or insect mouthparts) were very poorly preserved, and arthropod cuticle fragments were scarce. Charcoal and phytoclasts were other frequent constituents of the palynofacies (Fig. 2).

NON-POLLEN PALYNOMORPHS (NPP)

Chlorophyta; green algae

Botryococcus Kützing, 1849. *Botryococcus* spp. colonies present in the samples are of variable size, ranging from 100 to 150 µm, and appear as moderately degraded botryoidal colonies that lack clear cup shapes, and are highly fluorescent (Fig. 3A-C). They are proportionally more abundant in samples 09-243 and 09-262, less proportionally abundant in sample 09-234, and are absent in samples 09-242 and 09-255 (Fig. 2). *Botryococcus* colonies of the planktonic green algal genus are well-known as fossils, extending back to the Precambrian (Batten & Grenfell 1996). *Botryococcus* is most often found in freshwater bogs, temporary ponds, pools, and lakes, however, considerable abundances are known to occur in variable saline/brackish water supporting its cosmopolitan habitat (Batten & Grenfell 1996; Senousy *et al.* 2004; Kumar *et al.* 2017 and references therein).

Although *Botryococcus* coenobia have little biostratigraphic value, the fossil forms can be used, through analogy with the living microalga, to elucidate palaeoecological and climatic conditions and palaeoenvironmental reconstructions (e.g. Guy-Ohlson & Lindström 1994). In addition, they generate liquid hydrocarbons (Batten & Grenfell 1996).

Chlorophyta

Palambages Wetzel, 1961. *Palambages* is a fossil taxon that refers to simple groupings of small spheroidal to ovoidal cells; individual cells are typically 7-10 µm in diameter (Fig. 3D-G). In the studied material, *Palambages* occurs repeatedly in all samples, except for sample 09-243; it is most abundant in sample 09-262 (Fig. 2). The biological affinities of *Palambages* are uncertain, however, they are generally considered to be affiliated to the Chlorophyta (e.g., Słodkowska 2004; Wainman *et al.* 2019), although their primary classification as incertae sedis cannot be entirely excluded (Wetzel 1961).

The oldest known fossil record of *Palambages* is described from the Oxfordian to Albian Pemba Formation in Mozambique (Smelror *et al.* 2008). Despite their repeated occurrence in Mesozoic basins worldwide (e.g. Wetzel 1961; Gocht & Wille 1972; Słodkowska 2004; Wainman *et al.* 2019; among others), this is the first report of *Palambages* from the Mesozoic

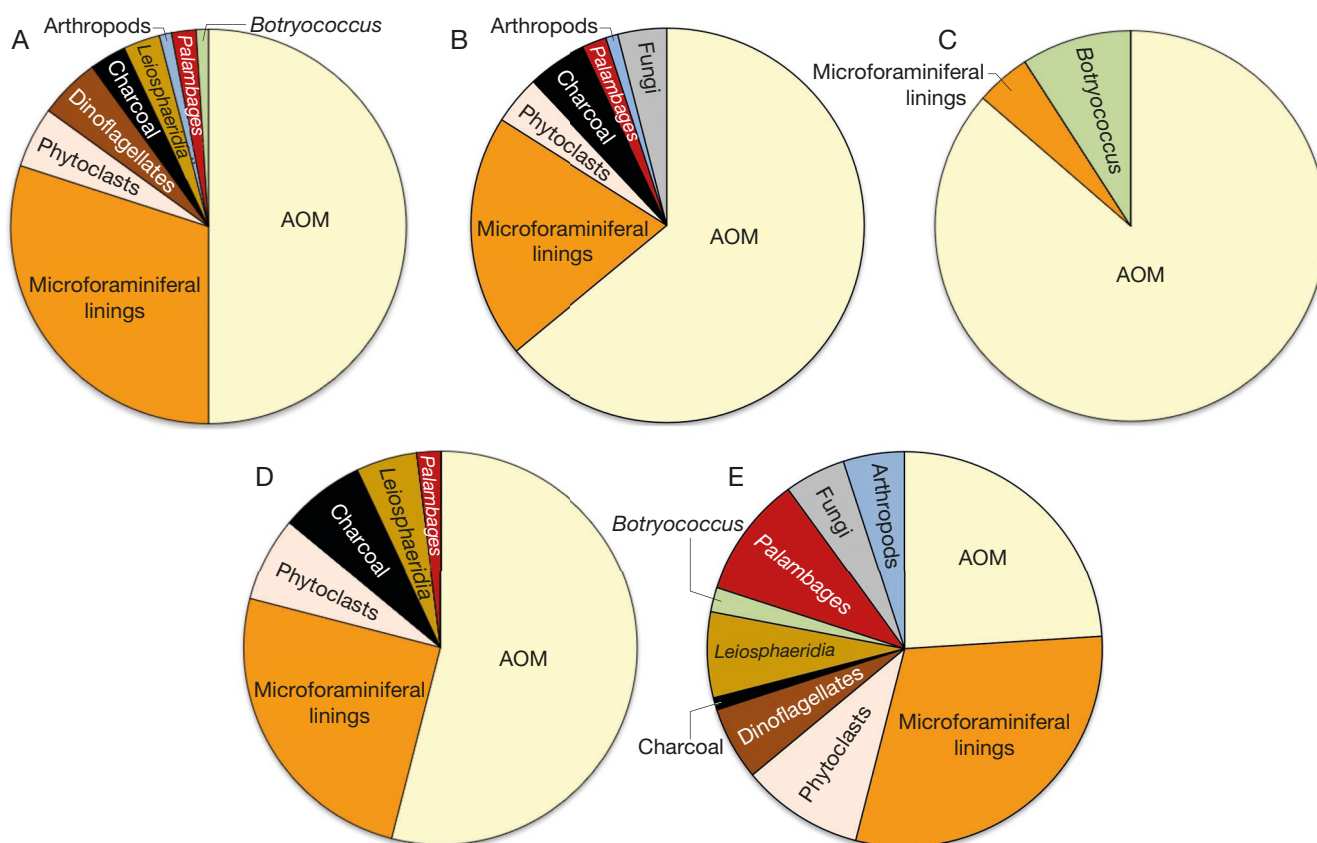


FIG. 2. — Quantitative representation of the percentages for the recorded NPPs in the studied samples: **A**, 09-234; **B**, 09-242; **C**, 09-243; **D**, 09-255; **E**, 09-262.

basins of Iraq. Previous occurrences of these sporadic colonial cysts were likely disregarded or ignored.

Prasinophyceae; Chlorophyta, green algae

***Pterospermella* Eisenack, 1972.** A single *Pterospermella* sp. was found in sample 09-262. It is characterized by a spherical to ovoidal central body surrounded by a flat, membranous equatorial wing lamella, with a maximum diameter of 30 µm. However, this specimen lacked sufficient characters for robust species-level identification (Fig. 3H).

***Leiosphaeridia* Eisenack, 1958.** Leiosphaerids are considered to be algal cysts produced in the course of the reproductive phase of the life cycle; an assumption that is reinforced by the occurrence of an encystment opening (Moczyłowska 2008). *Leiosphaeridia* is known from the Precambrian to the present (Traverse 2007), and includes spheroidal to ellipsoidal, organic-walled microfossils of variable morphology, diameter, and wall thickness. The unicellular *Leiosphaeridia* are produced by planktic algae, with alternating sexual or vegetative generations in their life cycle (Moczyłowska 2008). Leiosphaerids are presumed to embody either several planktonic green algal species (e.g. Tappan 1980), photosynthetic protists (Traverse 2007), or other microorganisms of so far unidentified affinities (Moczyłowska *et al.* 2010). The eukaryotic algal origin of leiosphaerids has been suggested based on morphology, size, cell-wall, and palaeoecology

(Tappan 1980; Colbath & Grenfell 1995 and discussion therein). Based on the discussion above, and the suggestions from previous studies (e.g. Traverse 2007), they can no longer be referred to as acritarchs.

The recorded specimens from the Yamama Formation (Fig. 3L-O) are represented by bag-shaped, thin-walled, flattened, often collapsed, and sometimes folded palynomorphs in which the encystment opening is rarely preserved (e.g. Fig. 3O), with a maximum diameter of 35-40 µm in average. They are preserved in relatively similar proportions in samples 09-234, 09-255, and 09-262, and completely absent in samples 09-242 and 09-243 (Fig. 2).

DINOFLAGELLATE CYSTS (DINOPHYCEAE)

Dinoflagellates represent a major constituent of marine phytoplankton, mostly live in marine and are generally less diverse and abundant in freshwater conditions. They reproduce by producing distinctive zoospores and, during a resting phase, zygotic cysts (Beam & Himes 1980). Both the planktonic vegetative cells and cysts can be employed in palaeoenvironmental elucidation (Mudie *et al.* 2004) and biostratigraphy of Mesozoic and Cenozoic rocks (e.g. Williams *et al.* 2004).

In this study, dinoflagellate cysts were found to be poorly preserved and torn. However, it was possible to identify some species such as *Batioladinium micropodum* (Eisenack & Cookson, 1960) Brideaux, 1975, *Cribroperidinium* spp., *Subtilisphaera* spp. (Fig. 3I-K).

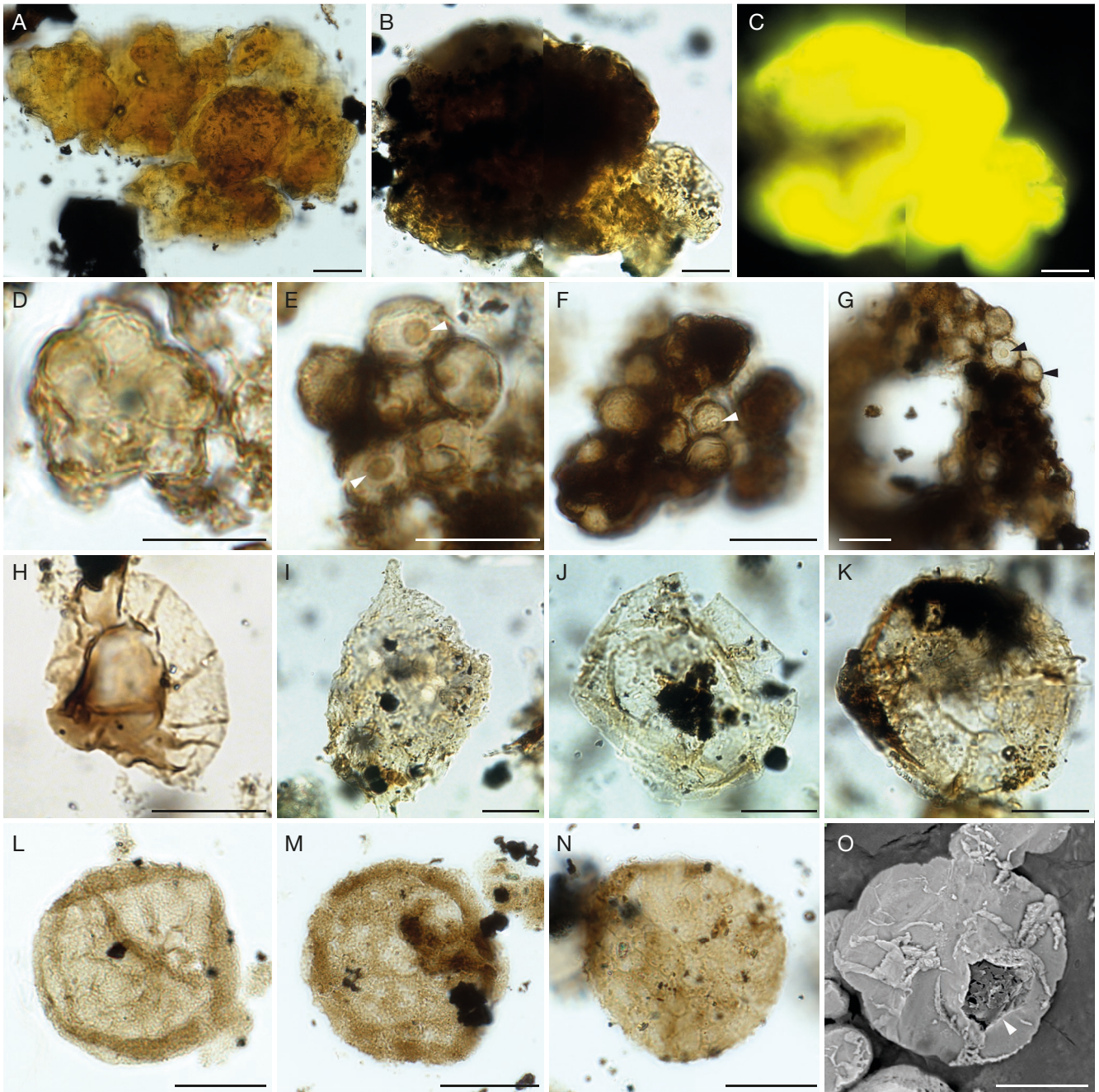


FIG. 3. — The palynological assemblage of the Yamama Formation: **A**, colony of degraded *Botryococcus* Kützing, 1849 seen in transmitted white light. Note characteristic globular outline and lustrous yellow colour; 09-262-2_P47; **B**, isolated coenobium of degraded *Botryococcus* colony seen in transmitted white light; 09-234-1_P35; **C**, colony of *Botryococcus* fluorescing under incident blue light illumination, the globular outline of the cells is very clear however, the cell cups are not clearly visible; 09-234_P35; **D**, *Palambages* sp., 09-242-3_P36; **E**, *Palambages* sp., 09-262-2_W40, arrow refers to loophole (= Schlüpfloch of Gocht & Wille 1972); **F**, *Palambages* sp., 09-262-3_G36, arrow refers to loophole (= Schlüpfloch of Gocht & Wille 1972); **G**, *Palambages* sp., 09-262-3_G40, arrows refer to loophole (= Schlüpfloch of Gocht & Wille 1972); **H**, marine prasinophyte phycoma of the genus *Pterospermella* Eisenack, 1972, 09-262-1_H53; **I**, dinocyst *Batioladinium micropodium* (Eisenack & Cookson, 1960) Brideaux, 1975, 09-234-1_R56; **J**, dinocyst, 09-234-1_M50; **K**, dinocyst, *Cribroperidinium* sp., 09-234-1_N53; **L**, *Leiosphaeridia* sp., 09-255-3_G53; **M**, *Leiosphaeridia* sp., 09-262-3_T37; **N**, *Leiosphaeridia* sp., 09-234-3_S51; **O**, *Leiosphaeridia* sp., 09-255, arrow points to a possible encystment opening. Scale bars: 20 µm.

MICROFORAMINIFERAL LININGS

In this study, microforaminiferal linings (Fig. 4A-P) are composed of a series of cells of variable size and preservation status. Foraminiferal tests are built of chambers, which have cavities containing the cytoplasm within a surrounding firm mineral wall. Adjacent chambers are separated by septa but a

connection between septa is maintained by a hole or foramen. The first chamber, called the proloculus, is centrally developed and is commonly thicker than other succeeding chambers and is lost in some forms, while the second chamber is usually smaller than the proloculus. The size of succeeding chambers gradually increases; the last or terminal chamber appears to

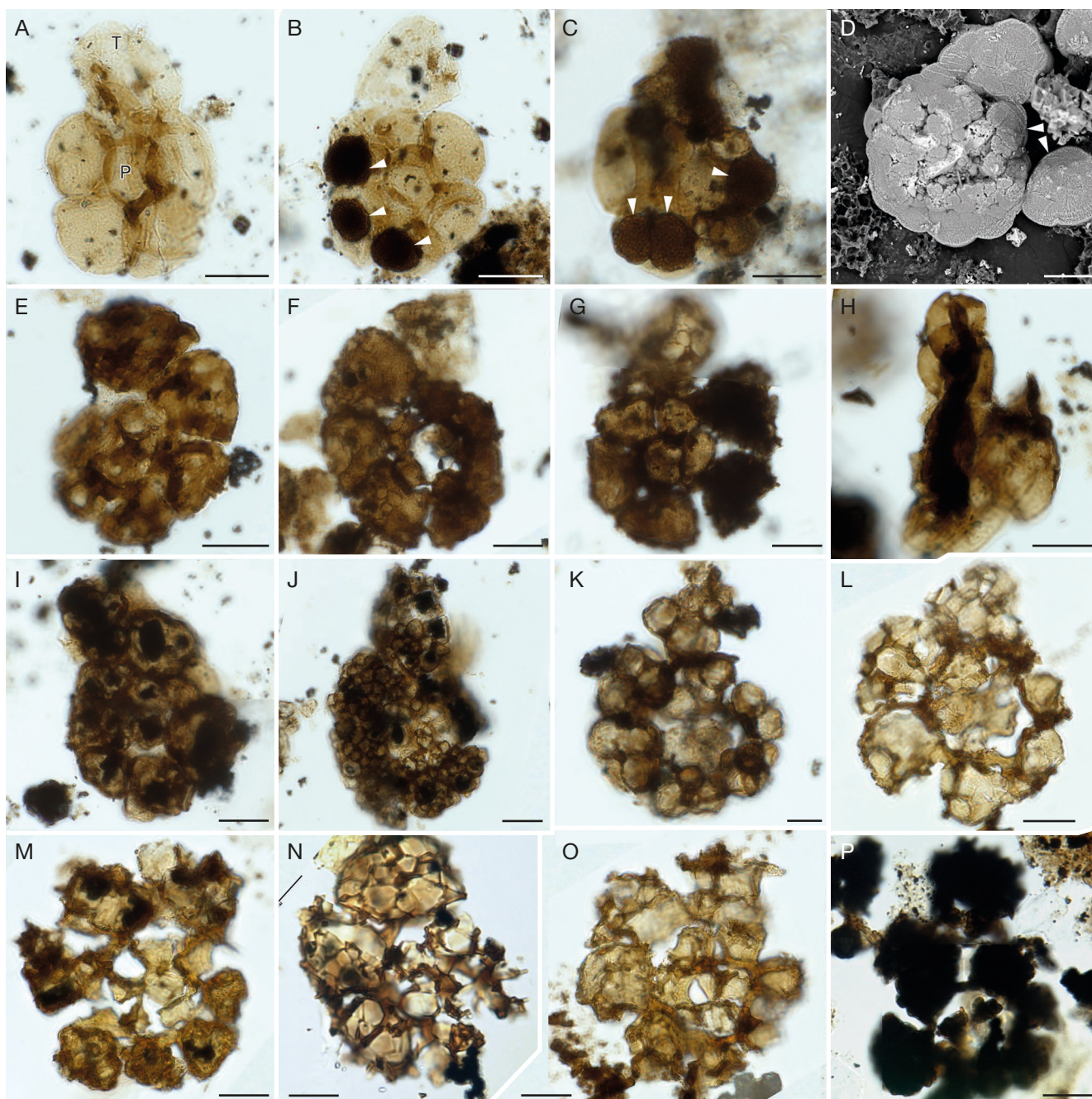


FIG. 4. — Photomicrographs of microfossil linings illustrating variable differences in the degree of pigmentation and preservation: **A**, coiled form, P points to proloculus and T refers to terminal last chamber, 09-234-2_K52; **B**, coiled form, arrows point to pyrites infills and pseudomorphs in the chambers of a foraminiferal test, 09-234-2_H45; **C**, coiled form, arrows point to Pyritospheres (Love, 1957) infills and pseudomorphs in the chambers of a foraminiferal test, 09-234-2_D49; **D**, coiled form, arrows point to pyrites infills and pseudomorphs in the chambers of a foraminiferal test, taken with SEM, 09-262-2; **E**, coiled form, 09-262-3_K45; **F**, coiled form, 09-262-3_Q49; **G**, coiled form, 09-262-3_R47; **H**, coiled form, 09-262-2_S43; **I**, coiled form, 09-234-2_L47; **J**, coiled form, 09-262-03_K41; **K**, coiled form, 09-262-3_M44; **L**, coiled form, 09-242-3_F36; **M**, coiled form, 09-242-3_L42; **N**, coiled form, 09-262-1_N41; **O**, coiled form, 09-242-3_Q50; **P**, coiled form strongly invaded with pyrite, 09-262-1_B44. Scale bars: 20 μ m.

be larger than the others and is thin-walled (Fig. 4A). In the investigated material, microfossil linings were preserved in a fairly large proportion in all samples and in a lesser amount only in sample 09-243 (Fig. 2). Morphologically, the recorded foraminiferal linings occur exclusively as coiled forms (both planispiral and trochospiral) and vary from 70 to 120 μ m in size (Fig. 4A-P).

Microfossil linings, a term coined by Wilson & Hoffmeister (1952), refers to the acid-resistant foraminiferal remains (less than 150 μ m in size), found in palynological preparations. It is the inner organic layer produced mainly by the calcareous and agglutinated benthic foraminifera (e.g. Mudie & Yanko-Hombach 2019), however, it may also be rarely produced by some planktonic forms (Arai &

Koutsoukos 1998) or throughout the planktonic phases of benthonic foraminifera (Davey 1978). The natural dissolution or breakage of calcareous microforaminiferal tests results in the liberation of their organic linings which maintain more or less the internal test morphology of the original foraminifers (Concheyro *et al.* 2014). The linings are composed of chitin, proteins, and polysaccharides, but some may have lignin compounds (Ní Fhlaithearta *et al.* 2013).

Fossil records of microforaminifera and observations of living foraminifera indicate the importance of these organic linings in micropalaeontological studies, protozoological, and even pollution investigations, however, their function is not yet clear (Mudie & Yanko-Hombach 2019 and citations therein). They are preserved in marine sediments ranging in age from the Lower Cambrian to Recent (e.g. Stancliffe 1989, 1996; Arai & Koutsoukos 1998; Winchester-Seeto & McIlroy 2006; Gutiérrez *et al.* 2016; Mudie *et al.* 2021a).

The generic and specific level assignment of microforaminiferal linings following the formal classification of foraminifera is not possible, except for purely morphological categorization (Stancliffe 1989). While they are not reliable biostratigraphic indicators, they are indicative of marine environments or marine input (coastlines and estuaries) which makes them suitable for providing environmental scenarios (e.g. Stancliffe 1989).

SCOLECODONTS

Scolecodonts represent acid-resistant, chitinous mouthparts of marine annelid worms in the form of jaws or maxillae. Fragments of these are frequently encountered in palynological slides from conventional macerations (Traverse 2007). In the Yamama samples, a single specimen has been identified as a potential scolecodont from sample 09-262. It has a maximum diameter of 90 µm and a light to medium brown colour (Fig. 5K). However, we cannot exclude that such a single record could be attributed to reworking or that it may be attributable to insects, rather than polychaete annelid, mouthparts.

ARTHROPODS

Fragments of chitinous arthropod cuticles (Fig. 5A-J) occur rarely in Yamama samples from R-167, Ru-158, and Zb-42 wells. Larger fragments exhibiting serrate setae, fragments of setae *in situ* and empty sockets in which setae and maybe other cuticular appendages were articulated (Fig. 5A-B, D-E) are rather rare. Isolated setae (Fig. 5C, F) and unidentifiable structures resembling arthropod cuticular appendages (Fig. 5G-J) also occur.

Based on the visible anatomical details it is not possible to decide whether these structures originate from marine (i.e., crustaceans) or terrestrial arthropods (e.g., insects). Considering the assumed depositional environment, it seems reasonable to suspect an origin from marine arthropods or at least terrestrial arthropods dwelling under the influence of marine input.

PALYNOFACIES

The palynofacies content of the studied samples yielded a homogenous composition dominated by AOM (24-95%), followed by phytoclasts and a smaller proportion of palynomorphs (5-10%), excluding NPPs. As previously mentioned, microforaminiferal linings are the most numerous palynomorph, occurring in nearly all samples (Fig. 2).

AOM INCLUDING RESIN

The AOM category is the most dominant palynofacies element among the studied samples of the Yamama Formation (El Atfy *et al.* 2016). AOM represents non-structured organic masses of dissimilar sizes, which are derived through microbial degradation of microplankton, algae, and cyanobacteria.

In our material, the recorded AOM mostly has a gelified, high-density, sheet-like aspect arranged in an irregular pattern that can be indicative of a terrestrial origin, as shown in Fig. 6D-E. These particles range from yellow to light brown in transmitted light and are mostly non-fluorescent with no palynomorph inclusions. However, some samples contain granular AOM types that can be indicative of a marine origin, as they are derived primarily from phytoplankton; e.g. Fig. 6C. These have pyrite inclusions and are black to dark brown in colour under white transmitted light. Resin particles (Fig. 6H) and resinous drops are also recorded. However, while the resin is generally rare, it indicates the input of plant material throughout the succession (Kumar *et al.* 2001).

PHYTOCLASTS INCLUDING MICROCHARCOAL

Phytoclasts are dominated by rare, badly-preserved wood, tracheids, and cuticles with common opaques that are generally lath-shaped, sometimes equidimensional, probably resulting from stems and root tissues. The opaque and lath-shaped phytoclasts can be interpreted as microcharcoal (Fig. 6I) produced by wildfires, which are chemically inert and can be transported over great distances into such a marine environment (e.g. Scott 2010).

PALAEOENVIRONMENT AND PALAEOECOLOGY INTERPRETATION

The effectiveness of NPPs for palaeoenvironmental interpretation has not been addressed in Iraq before, even though they occur in palynological preparations of most sediments. Given their worth as palaeoenvironmental indicators, these microorganisms provide significant data about palaeoecological and environmental changes that complement palynological data, resulting in the improved interpretation of past ecological and climate changes (Limaye *et al.* 2007 and references therein).

Furthermore, palynofacies analysis is a valuable tool that is sensitive to changes in oceanic current dynamics, sea-level fluctuations (via proximal versus distal indicators), temperature, and productivity of sea-surface waters (e.g. Götz *et al.* 2008). Unfortunately, their application in the reconstruction of Early Cretaceous palaeoenvironments in southern Iraq is

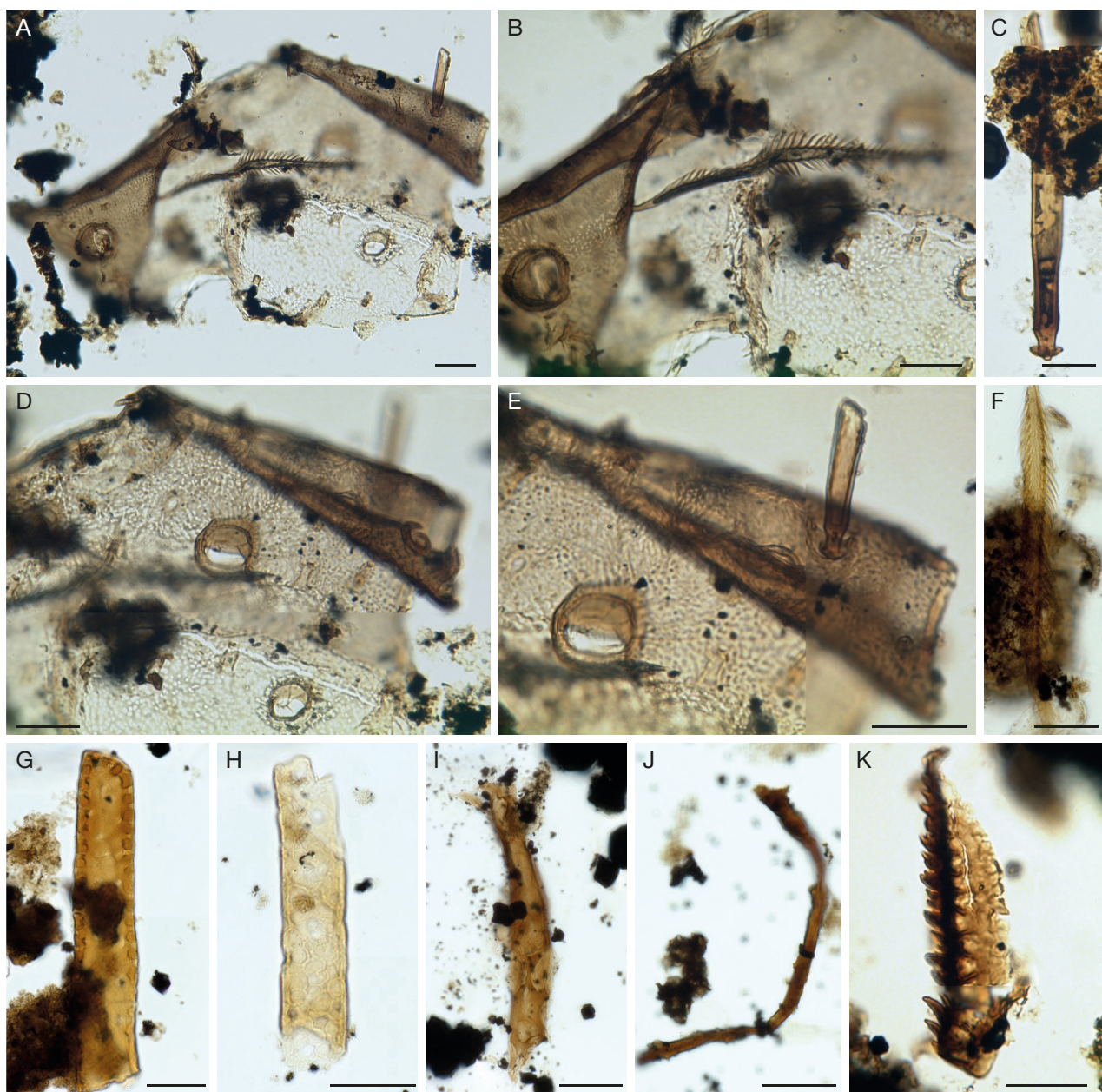


FIG. 5. — Arthropod cuticles: **A**, an overview of a large fragment of arthropod cuticle, 09-262-1_R29; **B**, detail of **A** showing a serrate seta, 09-262-1_R29; **C**, isolated seta (?), 09-262-1_R29; **D**, detail of **A** showing empty sockets in which setae and maybe other cuticular appendages were articulated, 09-262-1_R29; **E**, detail of **A** showing empty socket and fragmentary cuticular appendage in situ, 09-262-1_R29; **F**, isolated serrate seta, 09-262-3_L52; **G**, unidentifiable fragment of an isolated arthropod appendage (?), 09-255-2_H52; **H**, unidentifiable fragment of an isolated arthropod appendage (?), 09-255-2_L50; **I**, unidentifiable fragment of an isolated arthropod appendage (?), 09-234-3_L45; **J**, unidentifiable fragment of an isolated arthropod or insect appendage (?), 09-262-3_R47; **K**, scolecodont or insect mouthpart, 09-262-1_S53. Scale bars: 20 μm .

so far restricted to only a few studies (e.g. Al-Ameri & Batten 1997; El Atfy *et al.* 2016).

Among the NPPs, the presence or absence of microforaminiferal linings in sediments seems to be linked to the palaeoenvironment, which makes them a potential proxy for marine environments (Stancliffe 1989). Beyond the widespread use of microforaminiferal linings as markers of marine transgression in coastal lakes (van Geel 1978), they are frequently taken as indicators of brackish and marine environments in deltaic settings (Mudie *et al.* 2021a). Within the palynofacies present

in this study, most of the AOM appears to be of terrestrial origin, although deposited in a marine setting as dinocysts and microforaminiferal linings co-occur (e.g. Fig. 6C).

Similarly, Batten (1982) noted that microforaminiferal linings are often reasonably numerous in marine palynofacies that are dominated by AOM, as is the case for the studied samples (Fig. 6C). Piasecki (1986) noted the nearly total absence of microforaminiferal linings from Lower Cretaceous brackish marine sediments. Courtinat (1989) found an inverse relationship between the number of *Michrhystridium* (Deflandre,

1939) and microforaminiferal linings, a similar relationship has been recorded with dinoflagellates (Davies 1985). This is also the case for the studied samples from the Yamama Formation (Fig. 2). According to Stancliffe (1989), the highest concentrations of microforaminiferal linings recovered from modern environments seem to occur near upwelling currents containing abundant nutrients, in shallow water (less than 7 meters deep), or in waters of raised salinity. The water depth in which linings have been found ranges down to 9200 meters (Stancliffe 1989).

In palynofacies models, the occurrence or absence of microforaminiferal linings is thought to differentiate sediments produced in the transition from coastal lakes from those produced across the delta front, prodelta, and shelf sub-environments (Batten 1996; Hardy & Wrenn 2009). Microforaminiferal linings can be considered a reliable indicator of depositional setups of marine shelf, shallow or slope conditions (e.g. Stancliffe 1989; Oboh 1992), although they may be abundant in estuarine marshes of variable salinities (Batten 1996). These linings are common not only in carbonates but also in clastic shelf sediments deposited in warm, shallow marine nutrient upwelling areas that are not generally affected by terrestrial inputs (e.g. Powell *et al.* 1990).

Diagenesis of linings results in the formation of pyrite (mainly in Fig. 4) in the chambers through the activity of sulphate-reducing bacteria and the availability of iron and sulphur in anoxic burial conditions, at least as a microenvironment inside microfossils, where sulphate-reducing bacteria have an abundant supply of organic matter in shallow marine environments including oceanic, fluvio-deltaic settings with in situ detritus contributions (Álvarez-Iglesias & Rubio 2012). Pyrite formation in living benthic foraminiferal tests is also associated with anoxic conditions and can lead to test deformation (Seiglie 1973). Bacteria-related sulphate reduction in anoxic conditions is believed to be mainly responsible for pyrite occurrences in palynological macerals (Batten 1985), as is the case for our material that is drastically affected. This may happen in a variety of aquatic environments, within the water itself, and at or below the sediment-water interface (Wilkin *et al.* 1996). Pyrite is typically abundant in oil shales and hence in association with AOM which portrays their organic content (Batten 1985 and references therein).

Furthermore, pyrite in the Yamama samples is frequently recorded as framboids and other aggregate forms, of size, varying from 6 to 30 µm (Fig. 6K-L). However, round or spherical forms also occur. Some forms may represent steinkerns of fossils, or perhaps diagenetically overgrown framboids (welded pyrites). The abundant occurrence of pyrite framboids and other aggregates in the Yamama samples, especially diagenetically altered overgrown forms, implies diagenetic origin, deposited under anoxic conditions. Such an environment could be formed over larger areas within the sediment, or even as a microenvironment inside microfossils (Schallreuter 1984; Wilkin *et al.* 1996).

Within the Yamama samples, the presence of abundant well-preserved microforaminiferal linings indicates the absence of oxidising bottom water (Mudie & Yanko-Hombach 2019 and citations therein).

The microforaminiferal linings, along with dinoflagellate cysts, including *Batioladinium micropodum*, *Cribroperidinium* spp., and *Subtilisphaera* spp., indicate that deposition took place in a coastal or shallow marine setting with normal salinity (e.g. El Atfy 2021).

In the Yamama samples, the preservation of *Botryococcus* colonies differs considerably; extremely degraded remains are common and presumed to reflect significant microbial degradation in anoxic depositional and early diagenetic conditions (Batten & Grenfell 1996). Samples 09-243 and 09-243 contain a significant quantity of *Botryococcus* (Fig. 2), a cosmopolitan marine to fresh-water alga that is known as a petroleum source (Senousy *et al.* 2004).

The palaeoenvironmental significance of the fossil *Leiosphaeridia* is still controversial and requires wider discussion. According to Lebedeva (2008), their mass appearance may be characteristic of either deep-water, oxygen-deficient environments or coastal, lowered salinity, and oxygenated waters. Based on modern representatives of Chlorophyceae, *Leiosphaeridia* requires well-oxygenated open water conditions, easy access to the photic zone for photosynthesis and periodic access to bottom sediment to be able to encyst, their high abundances may be linked to regressive phase/low sea-level, slower sedimentation rate and decreased salinity (Radmacher *et al.* 2020 and references therein). Other studies suggest that *Leiosphaeridia* spp. are perhaps more resistant to aerobic conditions than some dinocysts (see Zonneveld *et al.* 1997) and may persist unaffected within deposits owing to their better tolerance of oxygen (Nikitenko *et al.* 2008). The oxygen level has an important influence on the composition of the palynological assemblage which may cause a reduction or even total absence of organic-walled palynomorphs within the rock (e.g. Zonneveld *et al.* 1997; Radmacher *et al.* 2020). Thus, variations in oxygen level could be responsible for the rare occurrence of dinocysts and denote the prevalence of an anoxic setting for the deposition of the Yamama Formation within the studied successions.

Palambages as a component of the recorded NPPs is not considered a noteworthy palaeoenvironmental indicator, even when common, as it has been documented from a wide range of depositional settings. Furthermore, they are also recorded from a variety of marine settings, including shelf to upper slope environments in Maastrichtian organic-rich mudstones in the Arctic (Firth & Clark 1998), and offshore cherts and flints of the Upper Cretaceous to Cenozoic of the Baltic (Wetzel 1961).

To sum up, based on the recorded NPP as well as palynofacies elements, it is possible to deduce that the studied strata within the Yamama Formation in southern Iraq were deposited under shallow marine, occasionally organic-rich (as demonstrated by the TOC wt.%; Table 1) and anoxic conditions. Moreover, the high abundances (except for sample 09-243 which exhibit lower concentrations) of microforaminiferal linings, as reflected from their modern analogues, suggest deposition near upwelling currents containing abundant nutrients, in shallow water, or waters of raised salinity (Stancliffe 1989). Similarly, along with microforaminiferal linings, dinocysts such as *Batioladinium*

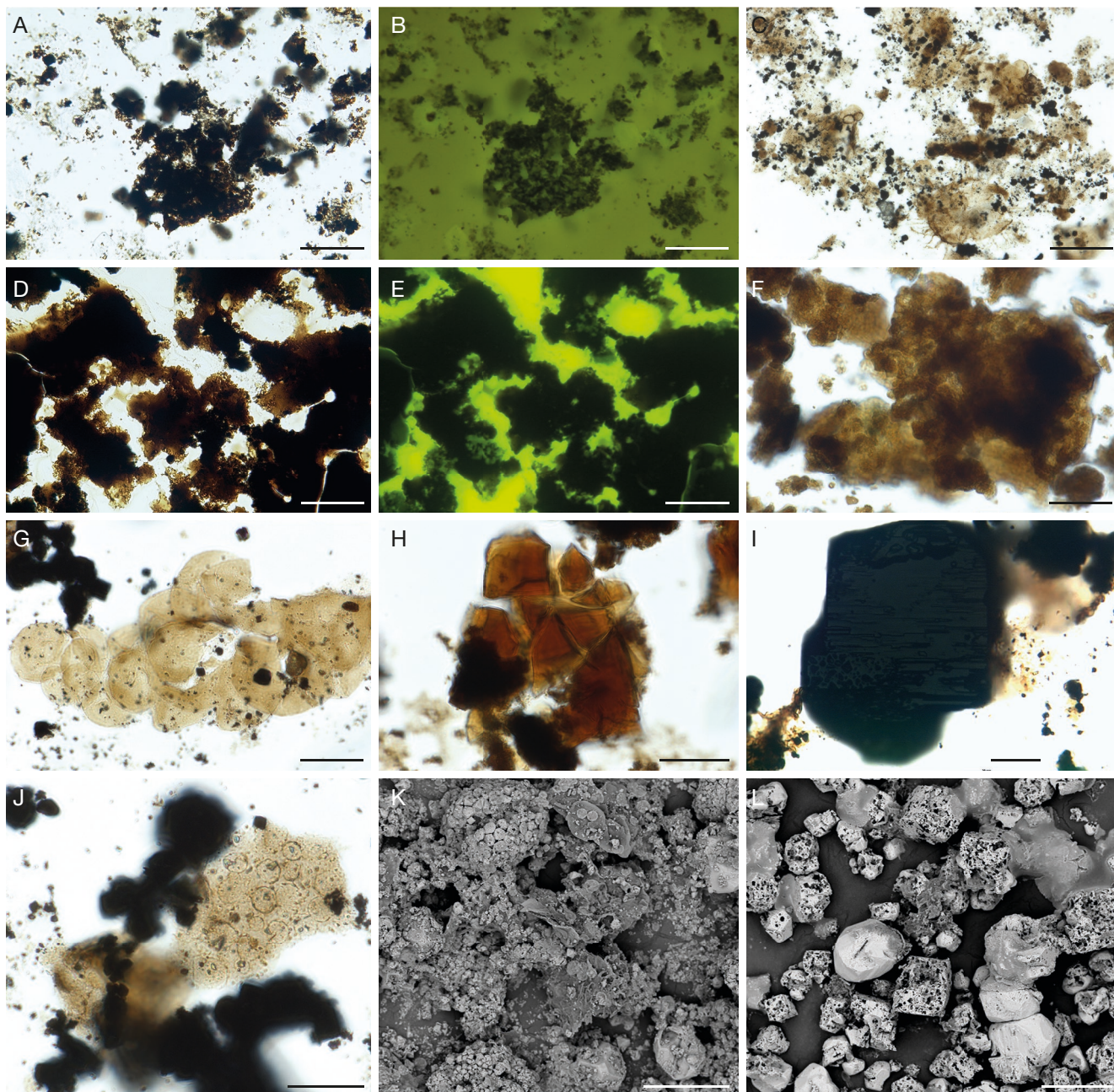


FIG. 6. — Palynofacies assemblages retrieved from the Yamama Formation: **A**, palynofacies dominated by AOM seen under transmitted light, 09-242-1_E43 (re-illustrated from El Atfy *et al.* 2016); **B**, non-fluorescent AOM; 09-242-1_E43 (re-illustrated from El Atfy *et al.* 2016); **C**, palynofacies assemblage composed mainly of fine granular, yellow to grey marine AOM, presumably of algal origin that contains pyrite crystals, dinocysts and microforaminiferal linings, 09-234-3_X42; **D**, transmitted light shows brown particles, membranes, thin films and amorphous substances, presumed to represent biodegraded terrestrial AOM, 09-243-1_E43 (re-illustrated from El Atfy *et al.* 2016); **E**, non-fluorescent AOM, 09-243-1_E43 (re-illustrated from El Atfy *et al.* 2016); **F**, gelified AOM, presumably of terrestrial origin palynofacies assemblages, 09-243-2_V33; **G**, *Leiosphaeridia* Eisenack, 1958 cluster, 09-234-3_Q49; **H**, resin particles seen in transmitted light showing different degrees of angularity and also cracking on the surface, 09-242-3_Q35; **I**, equidimensional opaque/microcharcoal particle, 09-262; **J**, *Palambages* relic structures in AOM matrix and opaque organic matter, 09-234-3_O48; **K**, framboidal pyrite, 09-234; **L**, partially oxidized pyrite aggregates, 09-255. Scale bars: 20 μ m.

micropodum, *Cribopteridinium* spp., *Subtilisphaera* spp. imply deposition in a coastal or shallow marine setting of normal salinity (e.g. El Atfy 2021). Additionally, the mass occurrence of *Leiosphaeridia* (except for samples 09-242 and 09-243) may infer either deep-water, oxygen-deficient environments or coastal, and freshwater-influenced waters and may be linked to regressive phase/low sea-level, slower sedimentation rate, and decreased salinity (Lebedeva 2008; Radmacher *et al.* 2020 and

references therein). Furthermore, gelified AOM of presumably non-marine origin suggests terrestrial input as evidenced also by the occurrence of cuticle and wood particles, including charred or opaque phytoclasts. Sample 09-243 yields a different NPP composition and only microforaminiferal linings, as well as *Botryococcus*, are present along with a very high AOM concentration (Fig. 2). Nonetheless, this yield represents more or less comparable depositional conditions as for other samples.

CONCLUSIONS

The following inferences are made from the palynological and palynofacies analyses of the Lower Cretaceous Yamama Formation in southern Iraq.

– Abundant assemblages of NPPs were recorded from different localities and strata of the Yamama Formation.

– Monotypic coiled forms of microforaminiferal linings were observed in subsurface samples from the R-167, Ru-158, Su-08, and Zb-42 wells in Southern Iraq.

– The recorded NPP assemblages suggest varied conditions were present during the deposition of the Yamama sediments. However, when integrated with palynofacies data, they suggest deposition in anoxic, inner to outer neritic conditions, in a position relatively near to the land, as evidenced by significant terrestrial input.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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