Paleoecology, palynofacies, thermal maturation and hydrocarbon source-rock potential of the Jurassic-Lower Cretaceous sequence in the subsurface of the north Eastern Desert, Egypt

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البيئة القديمة ، السحنة البالينولوجية ، النضوج العضوي الحراري والصخور المصدرية لتتابع الجوراسي والطباشيري السفلي التحت سطحي في شمال الصحراء الشرقية ـ مصر .

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يتناول هذا البحث نتائج السحنة العضوية البالينولوجية لصخور عصري الجوراسي والطباشيري السفلي التحت سطحية لآبار أبوحماد ـ ١، كبريت ـ ١ و IX - 71 - Q التي تقع في شمال الصحراء الشرقية بمصر . وقد تم تقسيم التعاقب الصخري إلى ثمانية تكاوين من أسفل إلى أعلى هي : رجبية، شوشة، بير مغاره، الخطاطبة، المساجد ، علم البويب، العلمين والخريطة .

وقد أسفرت دراسة أحافير حبوب اللقاح، الأبواغ، طحالب ذوات السوطين والبقايا النباتية إلى التعرف على سبعة سحنات عضوية تفسر بيئة الترسيب القديمة . وبناء عليه تم إستنتاج أن الجزء السفلي من متكون رجبية قد ترسب في بيئة شاطئية أو سبخة بينما الجزء العلوي من متكون رجبية ومتكون شوشة قد تم ترسيبهما في بيئة بحرية ضحلة من الرصيف القاري الداخلي (عمق أقل من ٣٠ مترا) في ظروف مناخية شبه إستوائية، في حين أن متكون بير مغارة قد ترسب في مياه بحرية تقع في الجزء الداخلي والأوسط من الرصيف القاري (عمق أقل من ١٠٠ متر) كما يعتقد أن متكون الخطاطبة قد ترسب في بيئة بحرية تقع في الرصيف القاري المتوسط والخارجي (عمق ٣٠ ـ ٢٠٠ مترا) ، بينما متكون المساجد (جوراسي علوي) قد تم ترسيبه في بيئة بحرية مفتوحة وعميقة نوعا من منطقة الرصيف القاري الخارجي والمنحدر القاري العلوي (عمق ١٠٠ ـ ٦٠٠ مترا) . ومع بداية العصر الطباشيري السفلي حدث تراجع للبحر مما أدى إلى ترسيب متكون علم البويب في بيئة بحرية ضحلة وقرب الشاطئ (عمق أقل من ٣٠ مترا) ، بينما متكون العلمين يعتقد إنه ترسب في بيئة ضحلة من منطقة الرصيف القاري المتوسط (٣٠ ـ ١٠٠ مترا) ، وأخيرا فإن متكون الخريطة (ألبيان سفلي) قد ترسب في بيئة ضحلة من الرصيف القاري الداخلي (أقل من ٣٠ مترا) .

وقد أدت دراسة التغير في لون أحافير الأبواغ والتبدل الحراري إلى تقسيم التتابع الصخري إلى سحنتين :

الأولى هي السحنة العضوية الغير ناضجة حرارياً وتشمل أعماق ١٣٠٨ ـ ١٩٥٠ متراً، ١٦١٥ ـ ٢٥١٥ متراً،
٦٥٥ ـ ٧٧٥ متراً في آبار أبوحماد ـ ١، كبريت ـ ١، IX - 71 - Q على الترتيب . بينما الثانية هي السحنة
العضوية الناضجة حرارياً على أعماق ١٩٥٠ ـ ٤٢٤٨ متراً، ٢٥١٥ ـ ٢٩٢٦ متراً، ٧٧٥ ـ ١٢٥٣ متراً في آبار
أبوحماد ـ ١، كبريت ـ ١، IX - 71 - Q على الترتيب .

هذا وقد أدت الدراسة إلى استنتاج الصخور المصدرية عالية الجهد لتوليد الزيت الخام وتنحصر في تتابع
الطفلة ذات النضوج العضوي الحراري الجيد من الجزء السفلي لمتكون المساجد ومتكون الخطاطبة والجزء العلوي
من متكون المساجد ومتكون الخطاطبة والجزء الأوسط لمتكون رجبية في بئر أبوحماد ـ ١ . بينما الصخور المصدرية
للزيت متوسطة الجهد تنحصر في الجزء العلوي من متكون المساجد في بئر أبوحماد ـ ١ ومتكون رجبية في بئر
كبريت ـ ١ والجزء الأوسط لمتكون الخطاطبة ومتكون شوشة في بئر IX - 71 - Q .

كما أمكن استنتاج الصخور المصدرية الناضجة والتي قد تولد الغاز الطبيعي وهي الجزء العلوي من متكون
رجبية في بئر أبوحماد ـ ١ ومتكون بير مغارة في بئر كبريت ـ ١ والجزء السفلي من متكون الخطاطبة ومتكوني
بير مغارة ورجبية في بئر IX - 71 - Q .

Key Words : Jurassic, Cretaceous, Paleoecology, Palynofacies, Thermal alteration, Source-rock, Masajid, Khatatba, Bir Maghara.

ABSTRACT

The Jurassic to Lower Cretaceous sequences in the wells Abu Hammad-1, Q-71-IX and Kabrit-1, north Eastern Desert of Egypt, have yielded palynofacies assemblages of varying composition. Seven palynofacies types which are environmentally controlled are identified and the source rock potential is evaluated.

Eight formations are paleoecologically studied using spores, pollen grains, dinoflagellate cysts and other particulate organic matter. The lower part of the Rajabiah Formation (Toarcian-Aalenian) was formed in shallow marginal marine or sabkha environment, while the upper part of the Rajabiah and the Shusha formations were deposited in shallow marine environment (inner shelf) under warm subtropical climatic conditions. The deposition of the Bir Maghara Formation is believed to be deposited in shallow marine environment of the inner to middle shelf. The deposition of the mixed clastic and carbonate sequence of the Khatatba Formation (Bathonian-Callovian) was took place in the middle to outer shelf conditions (30-100 m). The Masajid Formation (latest Callovian-Kimmeridgian) is a massive carbonates succession with intercalated shales that was deposited in normal marine conditions of the outer shelf to upper slope (100-600 m). The siliciclastic deposits of the Alam El Bueib Formation (Barremian-Aptian) were accumulated in near shore to inner shelf (<30 m) environment, under arid to semiarid conditions. The deposition of the Alamein Formation (Aptian) may have taken place in shallow marine environment of the middle shelf, while the clastics of the Kharita Formation (Lower Albian) may have been deposited in the inner shelf environment.

Spore/pollen colour is used to discriminate the órganic maturation levels and thermal alteration for the

studied sequences. Immature thermal facies is determined for depths 1308-1950 m in the Abu Hammad-1 well, 1615-2515 m in the Kabrit-1 well and 655-775 m in the Q-71-IX well. Mature thermal facies is determined for depths 1950-4248 m in the Abu Hammad-1 well, 2515-2926 m in the Kabrit-1 well and 775-1253 m in the Q-71-IX well.

Shales of the lower Masajid, Khatatba and the middle part of Rajabiah formations are supposed to have a high source potential for crude oil, while a moderate source-rock potential is determined for the upper Masajid Formation in the Abu Hammad-1 well, for the Rajabiah Formation in the Kabrit-1 well, for the middle part of the Khatatba and Shusha formations in the Q-71-IX well.

Gas-prone, mature source rocks are detected in the upper Rajabiah Formation in the Abu Hammad-1 well, in the Bir Maghara Formation in the Kabrit-1 well, in the upper and lower Khatatba, Bir Maghara and Rajabiah formations in the Q-71-IX well.

Introduction

It is clear that the Jurassic and Lower Cretaceous sequence was the target of oil companies since 1940 [1]. Since the discovery of significant hydrocarbon reserves in the Lower Cretaceous (Albian) (1973, Gupco, WD-19-1 well) and in the Jurassic of the Western Desert (1985, Khalda Petroleum Co., Salam-3x well), there has been a resurgence of economic interest in these rocks.

In recent years an awareness has developed among palynologists, both within the oil industry and in the academic community, that palynofacies analysis is primarily emphasis on paleoenvironmental analysis and to a lesser extent, the assessment of hydrocarbon source rock potential.

The present study is aimed at the palynological analysis of sedimentary organic matter encountered in samples from three deep wells in order to determine the nature of organic matter preservation, kerogen types, organic thermal maturation history and to give a rough estimation of the hydrocarbon generation potential.

Material and methods

A total of 113 samples taken from three wells, namely Abu Hammad-1, Q-71-IX and Kabrit-1, located in the north Eastern Desert, Egypt, east of Cairo (Fig. 1) has been investigated palynologically. The number of studied samples and particulars of each well are cited in the following table:

Well	Number of studied sample	Latitude°N	Longitude°E	Operator
Abu Hammad-1	42 ditch and 2 cores	30° 34' 07"	31° 50' 04"	IEOC
Q - 71 - IX	22 ditch	30° 19' 11"	31° 42' 34"	IEOC
Kabrit-1	45 ditch and 2 cores	30° 12' 17"	32° 29' 54"	Conoco
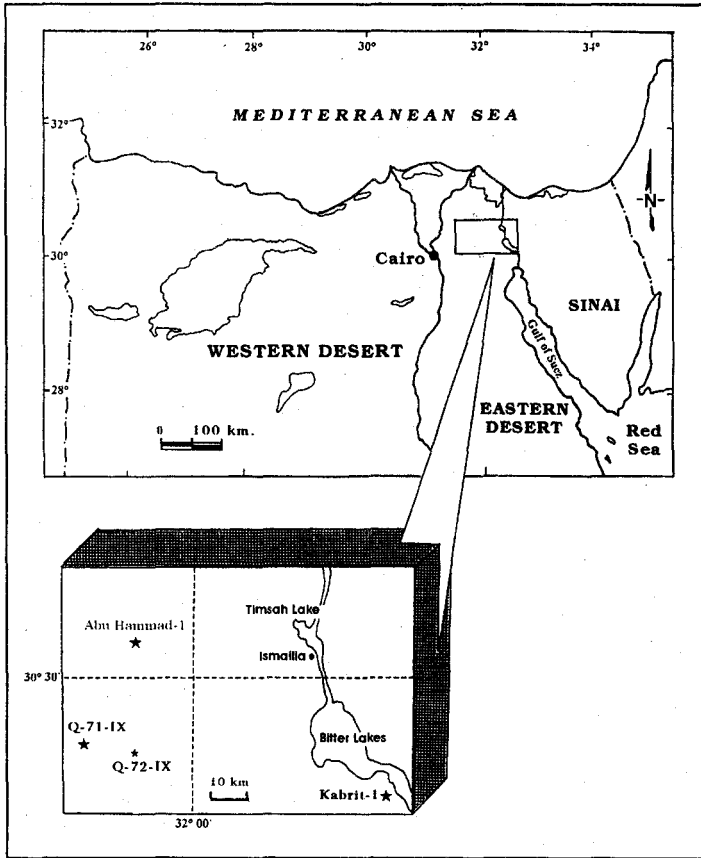
Fig. 1 - Location map for the studied wells.

Stage	Dinoflagellate Zone	Miospore Zone	Occurence in the studied wells
E. Albian	Subtilisphaera senegalensis-Dinopterygium cladoides C.R.Z.	Crybelosporites pannuceus-Afropollis jordinus-Tricolporopollenites A.Z.	
Aptian	Pseudoceratium securigerum R.Z.	Afropollis operculatus-Brenneripollis-Tricolpites spp. A.Z.	
Barremian	Pseudoceratium anaphrissum-Muderongia simplex C.R.Z.	Stellatopollis spp. Schrankipollis spp. A.Z.	
Kimmeridgian	Gochteodinia mutabilis R.Z.		
	Amphorula dodekovae T.R.Z.		
Oxfordian	Epiplosphaera bireticulata-Acanthaulax granuligera C.R.Z.	Cicatricosisporites spp. Contigisporites spp. A.Z.	
	Gonyaulacysta jurassica-Epiplosphaera reticulospinosa C.R.Z.		
	Wanaea digitata T.R.Z.		
Callovian	Ctenidodinium continuum-C. ornatum C.R.Z.	Verrucosisporites spp.	
Bathonian	Dichadogonyaulax sellwoodi T.R.Z	Converrucosisporites spp. Triloposporites spp. A.Z.	
Bajocian	Pareodinia ceratophora I.Z.		
Aalenian Toarcian	Unnamed zone	Classopollis / Circullina-Deltoidospora spp. A.Z.	

Fig. 1 - Proposed dinoflagellate and miospore zones for the Early Jurassic to Early Cretaceous of the studied wells, north Eastern Desert, Egypt

Each sample underwent maceration with dilute HCl, HF, and concentrated HCl respectively. Two random strew slides were made for each sample using Kaiser's Glycerol Jelly as mounting medium.

The kerogen slides were examined under a Zeiss Standard-25 Photomicroscope at 100x, 250x, and 400x magnification.

The palynological analysis was conducted through the following steps: 1) qualitative and quantitative analysis of organic particles; 2) assessment of palynofacies type; 3) assessment of kerogen type; 4) determination of spore colour; 5) assessment of Thermal Alteration Index (TAI); 6) evaluation of organic matter thermal maturation; and 7) analysis of the ratio of terrigenous to marine particles (Figs. 3-5).

All slides were counted for their organic particle content (palynomorphs, phytoclasts, opaques and Amorphous Organic Matter "AOM") using transmitted light microscopy. For each sample a first count (about 300 particles) focused on the classification of palynodebris in terms of abundant (>35%); frequent (16-35%); common (5-15%) and rare (<5%) (Figs. 3-5).

Palynostratigraphy

A summary of the palynostratigraphy of the studied wells is depicted in Fig. 2. Detailed palynostratigraphic analysis is beyond the scope of the present paper.

Palynofacies and kerogen classification

The visual petrographic kerogen analysis is very useful for determining the oil-gas potential of a new area [2-6]. On the other hand, organic geochemical kerogen analysis carried out by Rock Eval pyrolysis is a second, but more expensive, screening method [7].

The kerogen type classification followed herein is that of Tyson [8, 9] designed for routine investigation of source rock potentiality as follows:

1) Kerogen type I: Highly oil-prone material.

2) Kerogen type II: Oil-prone material.

3) Kerogen type III: Gas-prone material.

4) Kerogen type IV: Inert material.

For more details and characterisation refer to Tyson [9].

In the present study, the recognized particulate organic matter (POM) is categorized into four groups namely: a)

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palynomorphs: include all miospores, dinocysts, acritarchs, other algal fragments and microforaminiferal test linings; b) phytoclasts: include structured terrestrial plant fragments such as cuticle, wood tracheid and cortex tissues; c) opaques (black debris): oxidized or carbonized brownish black to black colour woody tissues including charcoal; (group a, b, and c are usually termed structured organic matter (SOM)); and d) amorphous organic matter (AOM): all particulate organic components that appear structureless at the scale of light microscopy, including bacterially-derived AOM, resins, and amorphous products of the diagensis of macrophyte tissues [9].

Accordingly, seven palynofacies types have been identified from the Jurassic-Lower Cretaceous sediments of the studied wells (Figs. 3-5), depending on the abundance of the four POM groups. These palynofacies types and their equivalent kerogen types and paleoenvironmental characterization are as follows:

Palynofacies 1 (terrestrial palynomorph facies):

This facies is characterized by the abundance of spores and pollen grains, common to rare phytoclasts, dinoflagellate cysts, opaque terrestrial material and AOM. Kerogen type: II, oil-prone material.

Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The abundance of sporomorphs and the occurrence of phytoclasts with common dinoflagellate cysts indicates near-shore, marginal marine environment. The dinoflagellate/sporomorph ratio generally decreases on shore and in especially depressed areas near deltas [10, 11].

Palynofacies 2 (marine phytoplankton facies):

Palynomorphs are dominated by dinoflagellate cysts and microforaminiferal linings, beside other algal remains. This palynofacies is also characterized by common to rare miospores, phytoclasts, opaques and AOM.
Kerogen type: II, oil-prone material.
Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The rich and diverse phytoplanktons suggests normal open marine environment. High dinoflagellate concentration should indicate inner part

of shelf to upper part of the continental slope, and high primary productivity [9, 10].

Palynofacies 3 (structured organic matter SOM facies):

Abundant phytoclasts consist mainly of well preserved structured terrestrial plant fragments such as cuticles and tracheids (plate 1, figs. 2, 4-6; plate 2, fig. 5; plate 3, fig. 4; plate 4, fig. 3). The palynomorphs are frequent to abundant the opaque plant fragments and AOM are also recorded in, this facies but in low frequencies.

Kerogen type: High number of phytoclasts with abundant sporomorphs, rare AOM and opaques reveals the kerogen type II to III, mainly gas-prone [8, 9]. Whilst high number of phytoclasts with abundant marine palynomorphs and common to rare AOM and opaques reveals the kerogen type II, oil-prone. An abundance of this matter in siltstone and shale is generally taken to indicate source potential for gas rather than oil regardless of its level of maturation [12, p. 592].
Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The contents of this facies reflect the proximity to a terrestrial source and vicinity of active fluvio-deltaic sources and oxidizing situations [9, 13]. Relatively large pieces of cuticles as well as entire leaves are especially characteristic of prodelta facies [14, 15]. Moreover, the abundance of cuticles can be related to the high energy parts of submarine fan system, especially the channel sandstones [13, 16].

Palynofacies 4 (opaque terrestrial and palynomorph facies):

This facies is characterized by the abundance of opaque terrestrial fragments and frequent to abundant palynomorphs. Phytoclasts and AOM are rare.
Kerogen type: III, gas-prone material.
Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The low frequency of dinoflagellate and microforaminiferal linings relative to terrestrial input infer the near-shore depositional environment. This is confirmed by the low diversity and high density of dinoflagellate species. The high ratio of
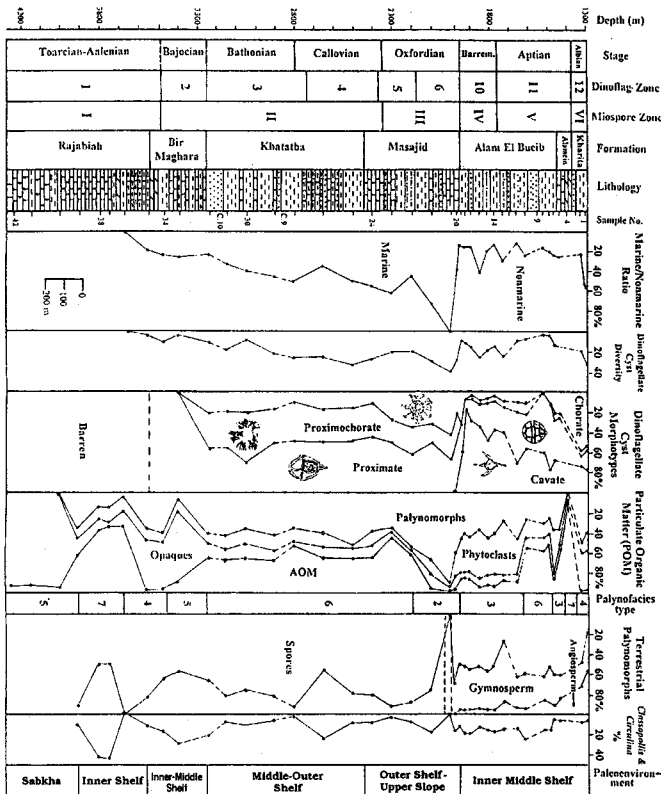
Fig. 3 : Vertical trends in marine/nonmarine %, dinoflagellate cyst diversity, dinoflagellate cyst morphotypes, particulate organic matter (POM), terrestrial palynomorph %, Classopollis & Circulina % and the proposed paleoenvironment in the Jurassic to Lower Cretaceous of the Abu Hammad-1 well.
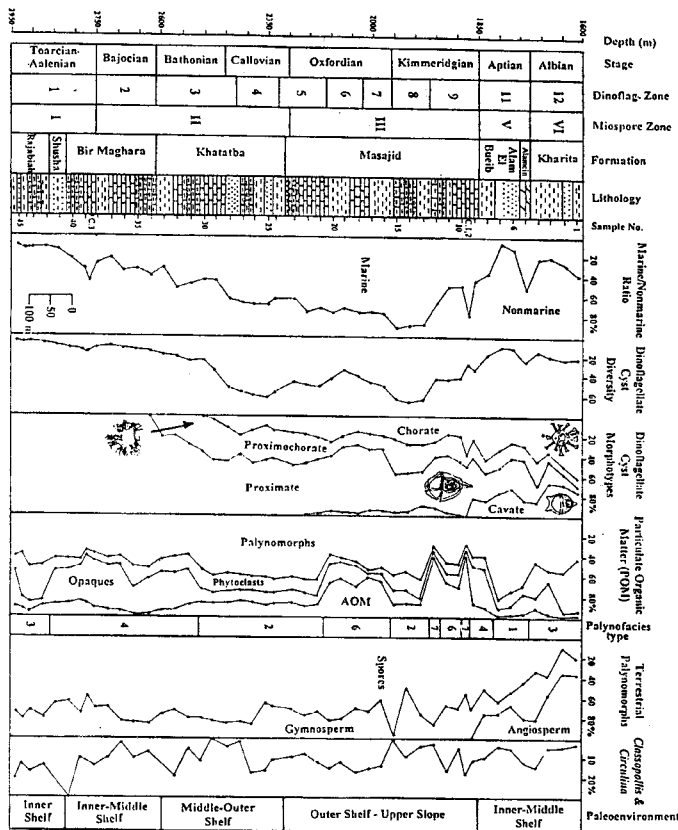

Fig. 4 : Vertical trends in marine/nonmarine %, dinoflagellate cyst diversity, dinoflagellate cyst morphotypes, particulate organic matter (POM), terrestrial palynomorph %, Classopollis & Circulina % and the proposed paleoenvironment in the Jurassic to Lower Cretaceous of the Kabrit-1 well.

opaques often results from post-depositional oxidation or prolonged transport of woody particles [9].

Palynofacies 5 (opaque terrestrial facies):

Abundant opaque fragments defined as dark brown to black colour with frequent to abundant pyrite. The pyrite in this facies may be large to medium crystals or framboidal. The palynomorphs and phytoclasts are rare. The AOM is rare to common with fine low relief.

Kerogen type: IV, inert material.

Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The dominant opaque category is interpreted as having a land plant origin [17]. The distribution of these allochthonous fragments is mainly controlled by hydrodynamic processes and sorting according to their buoyancy [18, 19, 20]. In some samples, the opaque fragments which are ill-sorted, non-equidimentional and diluted by overall AOM, phytoclasts
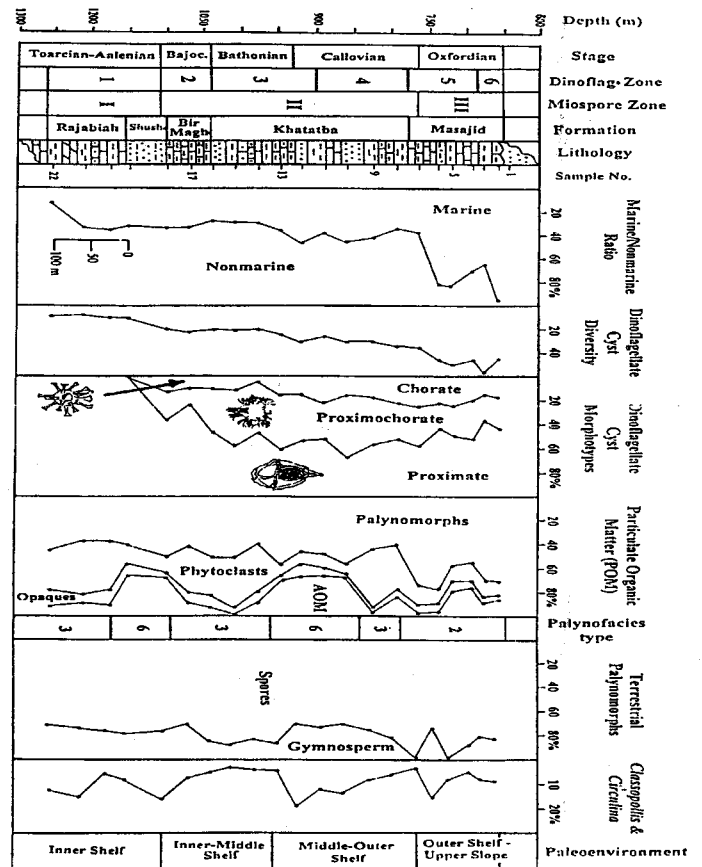

Fig. 5 : Vertical trends in marine/nonmarine %, dinoflagellate cyst diversity, dinoflagellate cyst morphotypes, particulate organic matter (POM), terrestrial palynomorph %, Classopollis & Circulina % and the proposed paleoenvironment in the Jurassic of the Q-71-IX well.

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and palynomorphs indicate deposition in turbulent shallow-marine water. Whilst, in some other samples, the opaque terrestrial is mainly of small size fractions <30 which may indicates wind-blown material in an inner to middle shelf environment [21, 22]. However, the high percent of pyrite suggests reducing conditions and/or distal-anoxic facies.

Palynofacies 6 (palynomorphs and AOM facies):

Abundance of AOM together with abundant to frequent palynomorphs. AOM is described as fine to gromose with moderate to high relief. The colour of AOM in this facies ranges from pale yellow to orange. Resin is common to frequent. The phytoclasts and opaques are rare to common and large to medium crystals of pyrite are also recorded.

Kerogen type: High AOM preservation with phytoclasts and moderate to frequent dinoflagellates and sporomorphs reveals kerogen type I-II, oil-prone material.

Occurrence: see Figs. 3-5.

Proposed paleoenvironment: The abundance of AOM with high percentage of palynomorphs (dominated by terrestrial sporomorphs) infer shallow water environment.

Palynofacies 7 (amorphous organic matter AOM facies):

This facies is characterized by abundance of fairly well preserved, yellow, gromose, high relief AOM. The palynomorphs, phytoclasts and opaques are rare to absent.

Kerogen type: I, highly oil-prone material.

Occurrence: see Figs. 3-5.

Proposed paleoenvironment: AOM is produced as organic aggregates derived from dissolved organic matter. It is also produced by benthic filamentous cyanobacteria of shallow waters and by benthic and pelagic sulphur bacteria of oxygen deficient environments [23]. Carbon isotopic evidence indicates that all typical marine AOM is ultimately phytoplankton derived [8]. Generally, the increase of amount of AOM indicates reducing conditions, distal dysoxic-anoxic shelf [8, 24].

Paleoenvironmental regimes

The paleoenvironmental reconstruction of the studied area throughout the Jurassic to Lower Cretaceous and the trends in rising and falling sea-levels can be deduced from the palynofacies parameters as for instance the marine/nonmarine ratio, dinoflagellate diversity, cyst morphotypes, type of particulate organic matter and Classopollis-Circulina percentage of the total sporomorphs.

All these parameters are summarized and illustrated in Figs. 3-5. Therefore, near-shore, inner shelf (<30 m), middle shelf (30-100 m), outer shelf (100-200 m) and upper slope (200-600 m) paleobathymetric depths can be inferred for the deposition of the encountered rock units as given below:

1. Rajabiah Formation (Toarcian-Aalenian)

Is represented in the three wells, but reaches a maximum thickness in the Abu Hammad-1 well (about 733 m). The lower part of the Rajabiah Formation in the Abu Hammad-1 well (interval 3903-4248 m) is barren of palynomorphs. It consists mainly of evaporite or sabkha deposits (anhydrite and limestone) and contains only opaque terrestrial fragments. Therefore, it seems possible that the deposition of this part took place in shallow marginal marine or sabkha environment. In the same well, the overlying interval (3552-3903 m) is equivalent to the encountered parts of the Rajabiah Formation in the Kabrit-1 (66 m) and Q-71-IX (98 m) wells, and is composed essentially of shaly limestone which contains terrestrial miospores dominated by Classopollis and Circulina spp. which reflects near shore to inner shelf environment. The AOM in this interval is derived from degradation of terrestrially-derived material as documented from the presence of a mixture of miospores, woody debris and cuticular fragments.

This interval is also characterized by frequent dinoflagellate cysts (10-39%), dominated by Parvocysta ampulla, Phallocysta eumekes, Valvaeodinium cf. armatum and Mancodinium spp. The dinoflagellate cysts are represented mainly by cavate (29-79%) and proximate cysts only in the Q-71-IX and Kabrit-1 wells. Dinoflagellate species diversity is low and relatively uniform throughout the Toarcian-Aalenian which is represented by the upper part of the Rajabiah Formation. The maximum species diversity is about 15 species/sample.

Accordingly, shallow marine environment (inner shelf) is inferred for the deposition of this part as documented from the predominance of terrestrial elements over marine one, low dinoflagellate species diversity, abundance of thick walled cysts of the cavate and proximochorate and the absence of chorate cysts. Kerdany & Cherif [25] and Keeley [26] assumed that the thickly bedded limestone of the Rajabiah Formation represent a limited transgressive phase.

During the Toarcian-Aalenian, warm subtropical climatic condition prevailed as concluded from the high percentage (10-44%) of Classopollis and Circulina pollen [27] and from the deposition of sabkha in the lower part of the Rajabiah Formation.

2. Shusha Formation (latest Toarcian-Aalenian)

This clastic unit is represented in the Kabrit-1 and Q-71-IX wells. In the Abu Hammad-1 well, it is represented by the carbonate facies belonging to the Rajabiah Formation. This is because the Abu Hammad-1 well is geographically located northwards in a deeper environmental setting.

It seems possible that the deposition of the sandstone and shale of the Shusha Formation took place in a shallow marine (inner shelf) conditions. However, Keeley & Wallis [28] and Keeley [26] assumed that the Shusha Formation represents a regressive phase. The palynofacies contents in this formation is very similar to those in the upper part of the Rajabiah Formation.

3. Bir Maghara Formation (Late Aalenian-Late Bajocian)

It is composed essentially of thin carbonate beds intercalated with shales. The dinoflagellate cysts are slightly increased (23-40%) relative to the Toarcian-Aalenian sediments. The proximate cysts become abundant (~95%) in some places and the cavate cysts decreased in comparison with the Toarcian-Aalenian assemblage. In addition, the first proximochorate and chorate cysts appear as shown in Figs. 3-5. Diversity of dinoflagellate cyst species is slightly uniform, but higher than in the Toarcian-Aalenian sediments.

The dinoflagellate assemblages contain common *Pareodinia ceratophora, Korystocysta* spp. *Dissiliodinium willi, Mancodinium semitabulatum, Cleistosphaeridium* spp. and *Ctenidodoinium* spp.

The microforaminiferal linings are also represented (1-2%) in the Kabrit-1 and Q-71-IX wells and absent from the Abu Hammad-1 well.

The terrestrial palynomorphs include abundant pteridophytic spores (42-57%) such as *Concavissimisporites, Converrucosisporites, Verrucosisporites* beside the psilate spores. The gymnosperm pollen (9-32%) are dominated by *Classopollis, Circulina, Exesipollenites,* and In-aperturopollenites.

Due to the slightly increase of dinoflagellate cysts number and diversity, a more offshore facies than in the Toarcian-Aalenian is recorded. This conclusion is supported by the deposition of marine carbonates of the Bir Maghara Formation [25]. Accordingly, an inner to middle shelf

environment is deduced for the deposition of the Bir Maghara Formation.

4. Khatatba Formation (Bathonian-Callovian)

The Khatatba Formation is a mixed clastic and carbonate sequence. Its thickness varies considerably, reaching the maximum (~2000 m) in the Gebel Rissu Basin (west of Cairo), then decreased in thickness to the east and west. In Sinai, it is usually about 500 m thick [29]. In the studied area its thickness increases northwards toward the Abu Hammad-1 well (810 m), presumably the result of marginal marine and continental shelf depositional relief.

Through the Khatatba Formation, palynofacies types are also varied both laterally from well to another and vertically in the same well, generally represented by palynofacies type 2, 3, and 6 which reflect continental shelf environment. It is characterized by frequent dinoflagellate cysts (23-50%) and rare microforaminiferal linings (~2%). Dinoflagellates are dominated by ctenidodinioid cysts (*Ctenidodinium combazii, C. ornatum,* and *C. continuum) Dichadogonyaulax sellwoodii,* and *Korystocysta kettonensis/gochtii.* The cyst morphotypes are dominated by proximate and prox-imochorate cysts, whereas, chorate cysts are common. Cavate cysts are absent.

The pteridophytic spore are abundant (38-63%) represented by *Verrucosisporites, Converucosisporites* and *Concavissimisporites.*

The gymnosperm pollen become less common than Bajocian (10-26%) represented by *Classopollis, Ciculina, Inaperturopollenites* and *Exesipollenites.*

Accordingly, middle to outer shelf condition is suggested for the deposition of the Khatatba Formation. This conclusion is supported by the occurrence of *D. sellwoodii/ Korystocysta* spp. (low relief ornamentation) which favoured restricted marine condition [30], whereas, *C. combazii* (heavily ornamented cyst) populated open marine, stable (in term of temperature and salinity) conditions [31, 32].

In the upper part of the Khatatba Formation (most of the Callovian) the marine/nonmarine ratio increased and the marine phytoplankton dominated over the terrestrial elements. This indicates a transgressive phase during the Early Callovian and increase in the offshore direction. According to Haq et al. [33], the Early Callovian on a global scale represents the transgressive event starting in the latest Bathonian. This interpretation is also supported by the widespread shelf carbonate deposition in the Callovian in

northeastern Egypt as reported by Kerdany & Cherif [25] and Keeley [26].

Tropical to subtropical climatic conditions still prevailed during the sedimentation of the Khatatba Formation.

5. Masajid Formation (latest Callovian- Oxfordian-Kimmeridgian)

The Masajid Formation is a massive shelf carbonate complex with intercalated shales. The thickness increased northwards with a maximum thickness in the Abu Hammad-1 well (490 m) and a minimum thickness in the Q-71-IX well (125 m). The variations in preserved thickness are largely a function of the local variations in the severity of Cimmerian erosion (Late Jurassic-Early Cretaceous) in the Abu Hammad-1 and Kabrit-1 wells, and/or clysmic erosion (Late Oligocene) in the Q-71-IX well.

The marine/nonmarine ratio is at maximum of the entire successions (40-100%, Figs. 3-5). A remarkable increase in dinoflagellate cysts of the chorate morphotypes (20-42%), represented by *Systematophora* and *Cleistosphaeridium* spp., proximate cysts (30-50%) represented by *Cribroperidinium, Gonyaulacysts, Pareodinia* and *Gochteodinia*, proximochorate cysts (15-30%) as *Histiophora, Amphorula* and *Epiplosphaera*, while, cavate cyst morphotypes are rare (0-7%) represented by species of *Glossodinium* and *Scriniodinium*.

Terrestrial palynomorphs are dominated by pteridophytic spores (8-40%) represented by *Contignisporites, Cicatricosisporites, Impardecispora,* and psilate trilete spores. Gymnosperm pollen are rare to common (3-12%) as in the underlying deposits.

The rich and diverse dinoflagellate cysts in the Masajid Formation suggest more open and deeper shelf environments than in the Callovian of the underlying Khatatba Formation.

As documented by several authors [8, 9, 34], the high dinoflagellate cysts concentration should be equated with outer part of shelf to upper part of continental slope, probably not particularly deeper. Accordingly, the Masajid Formation may have been deposited in normal marine conditions of the outer shelf to upper slope (100-600 m).

On the other hand, the change in the marine element concentration, dinoflagellate cyst morphotypes is resulted from the continuos fluctuation in sea level which in turn led to sedimentary facies change from massive carbonates to shale interbeds which is a characteristic phenomenon of the Masajid Formation. This conclusion was emphasized before by Kerdany & Cherif [25]; Keeley et al. [29]; Keeley & Wallis [28]; Keeley [26] and Haq et al. [33] on a global scale.

Sediments of the Masajid Formation are also characterized by the low percentage of phytoclasts and opaques with moderate to high AOM (but generally less than palynomorphs). This reflects high productivity and more reducing condition.

Generally, the palynofacies types in the studied Masajid Formation are recorded as type 2, 6 and 7 (Figs. 3-5).

At the end of the Jurassic a widespread regression occurs which was also reported by several workers in Egypt [25, 26, 35]. They also noted that this great regression at the end of the Jurassic corresponds to a global eustatic change in sea level and it may be attributed to the tectonic events.

6. Alam El Bueib Formation (Barremian-Aptian)

The Alam El Bueib Formation is a siliciclastic unit of Early Cretaceous age (Neocomian-Aptian). The lower part of this formation (Neocomian succession) is absent from the studied wells, and the Barremian sediments are also not represented in the Kabrit-1 well. The Alam El Bueib Formation is the extensive continental deposition on the unstable shelf formed during a Tethys sea level low [26].

In the sediments of the Alam El Bueib Formation, the nonmarine palynomorphs dominate (60-80%) over the marine phytoplanktons (Figs. 3-5). Dinoflagellates are mainly dominated by cavate (~60%) and proximate (~35%) cyst morphotypes, while chorate cysts are rare to common. Dinoflagellate species diversity is low and fluctuated around 20 species/sample.

The Alam El Bueib Formation is characterized by palynofacies 1, 3, 4 and 6.

Generally, decrease of marine elements, low species diversity and high sporomorphs input indicate near-shore marine to inner shelf environment for the Alam El Bueib Formation in the Abu Hammad-1 and Kabrit-1 wells. This conclusion is supported by the abundance of cavate cysts which typically characterize the shallow marine environments as documented by several author [8, 36, 37, 38].

The common occurrence of *Classopollis* and *Ephedripites* pollen in this interval indicates arid or semi-arid climatic conditions.

7. Alamein Formation (Aptian)

The Alamein Formation "Alamein Dolomite" is a transgressive carbonate complex in northern Egypt, overlying the shale and sandstone of the Alam El Bueib Formation [39]. The Alamein Formation in the Abu Hammad-1 and Kabrit-1 wells is represented by dolomite and limestone, characterized by nearly the same palynomorphs and palynofacies parameters as the underlying Alam El Bueib Formation, except the increase in percentage of the marine elements (Kabrit-1 well, Fig. 4) and high ratio of chorate dinoflagellate cysts (20-40%), which may indicate a transgressive phase. Therefore, the deposition of the Alamein Formation may have taken place in shallow marine environment of the middle shelf. The presence of palynofacies 7 (AOM) in the Alamein sediments of the Abu Hammad-1 well supports this transgressive phase.

This interpretation is in agreement with the regional Aptian sea level highstand and flooding in eastern and western parts of Egypt [25, 26, 28, 40, 41], and with the global Aptian transgresion [33].

8. Kharita Formation (Lower Albian)

The Lower Albian sediments in the studied wells are represented by sandstone and shale of the Kharita Formation (part). It comprises intervals 1341-1308 m and 1707-1615 m in the Abu Hammad-1 and Kabrit-1 wells respectively.

In the studied wells, the marine elements include dinoflagellate cysts (20-50%) and microforaminiferal linings (1-5%). Common dinoflagellates are *Oligosphaeridium* spp., *Dinopterygium* spp., *Subtilisphaera* spp., and *Odontochtina* spp. The cysts are represented mainly by chorates (56%), cavates (11-30%), proximates and proximochorates (5-15%, in some intervals up to 30%).

The terrestrial palynomorphs are represented by 8-20%, with a maximum percentage of 37%. Mainly smooth trilete spores, common *Cicatricosisporites* spp., and *Crybelosporites pannuceus* are present. Pollen grains are represented by gymnosperms (19%), and angiosperms (22-48%), mainly *Afropollis* spp. and common *Tricolpites* spp.

The transition between Aptian to Albian in the studied wells is marked by the change in the lithologic facies from dolomite and limestone (Alamein Formation) to sandstone and shale of the Kharita Formation. This change is accompanied by a slight decrease of marine elements in numbers and diversity (Fig. 4).

Therefore, palynofacies 3 and 4 with abundant sporomorphs and low dinoflagellate species diversity suggests an inner shelf environment for the deposition of the Kharita Formation in the studied wells. An exception is the interval 1308 m in the Abu Hammad-1 well, where the marine elements become abundant which may suggest open marine environment but not deeper water.

The high abundance of chorate beside the cavate cysts, especially in Kabrit-1 well, suggests middle shelf environment. The remarkable increase of *Afropollis* in the Lower Albian sediments, indicates that its parent plants could be very abundant in coastal habitats [42], and tropical to subtropical climatic condition are suggested for this time interval.

Thermal Maturation Analysis

Major parameters controlling the generation of hydrocarbons are the type and amount of organic matter in the potential source rock and its organic maturation level [43]. Temperature is one of the most important parameters affecting hydrocarbon generation. Techniques used to interpret past thermal history of particulate organic matter in general include: palynomorph colour, spore translucency, vitrinite reflectance and fluorescence microscopy. Additinal methods applicable in specific situations include: electron spin resonance of kerogen, liquid inclusions in minerals, conodont colouration and infra-red spectral analysis [44-46].

In the present study, thermal Alteration Index (TAI) is deduced using the changes in spore colour with depth. TAI values were determined by comparing the spore colour (thin-walled psilate, trilete spores were chosen; plate 4, figs 4-7) with the pollen/spore colour chart of Pearson [47]. However, some samples show a wide range of TAI value (±1). therefore, the mean value is calculated. Generally, the TAI value increases with depth from 2-, 2, 2+, 3-, to 3 (Figs. 6-8).

The thick Jurassic shale and shaley limestone sequence (2300 m in the Abu Hammad-1. about 1100 m in Kabrit-1 and 650 m in Q-71-IX well) is overlain by thick strata (650-1900 m) of Cretaceous and Tertiary sediments. The

combined thickness of the Jurassic, Createceous and Tertiary in the present area of investigation is probably sufficient to provide the thermal requirements for the generation of hydrocarbon in the Jurassic shale and argillaceous limestone. This also would suggest that primary migration of Jurassic hydrocarbons began in the Cretaceous to Tertiary.

In the Abu Hammad-1 well, the Jurassic sequence is generally thermally mature, while the overlying Lower Cretaceous sediments are immature (Figs. 6-8). In Kabrit-1 well, only the Lower and Middle Jurassic sediments (lower part of Khatatba, Bir Maghara, Shusha and Rajabiah formations) are mature, while the overlying sequence (upper Khatatba, Masajid, Alam El Bueib, Alamein and Kharita formations) is immature. Although, the Jurassic sediments in Q-71-IX well were encountered in shallow depth (650-1300 m) in comparison with the Jurassic formations in Abu Hammad-1 and Kabrit-1 wells, the Lower and Middle Jurassic sequence is mature and this in turn suggests that a huge thickness of the Cretaceous and Lower Tertiary sediments which represent the hiatus between the Oxfordian - Oligocene were eroded as a result of the Late Oligocene tectonics (Clysmic erosion, [29]).

Generally, immature thermal facies is determined for depths: 1308-1950 m in the Abu Hammad-1 well, 1615-2515 m in the Kabrit-1 well and 655-775 m in the Q-71-IX well. While, mature thermal facies is determined for depths: 1950-4248 m in the Abu Hammad-1 well, 2515-2926 m in the Kabrit-1 well and 775-1253 m in the Q-71-IX well.

Hydrocarbon Source-Rock Potential

Several authors have dealt with the Jurassic hydrocarbon source-rock potentiality in northern Egypt [29, 46-57].

In the Western Desert, oil was recovered from the Jurassic sequence in deep wells, e.g., Minqar-1, Dawabis-1, Razzak-1, Razzak-13, and West Halif-1. Oil fluorescence was recorded in the Jurassic sediments of Sidi Barrani-1, Abu Subeiha-1, El Dabaa-1, Hamed-1, Qattara Rim-1, Natrun Gibli-1, Gebel Rissu-1, and Abu Roash-2 wells [49, 51]. Mixed amorphous and herbaceous type oil-prone source rock is characteristic to the area extends from Zarif-Ras Qattara to Sanamein-Sanhur, while amorphous type oil-prone source rock is characteristic to the area

between Alamein and Zebeida. The northern carbonate facies is characterized by having no source rocks [50]. The Khatatba coals contain high volumes of humic material, largely inertinite, and low proportions of liptinitic vitrinite and algal kerogen [57]. These latter components have been shown to be the source of the Western Desert oils.

Little attempt have been done to evaluate the hydrocarbon potential of the Jurassic sequences in the north Eastern Desert. Of these are Khalil & Moustafa [58], and Abd-Allah & Bakry [59]. The later concluded that the shales of the Wadi El Natrun and Khatatba formations are potential source rocks.

Organic geochemical studies carried out by the operating companies showed the following values of the measured vitrinite reflectance (Ro) in Abu Hammad-1 and Kabrit-1 wells.

Well	Depth	Ro	Hydrocarbon phase according to Lopatin [60] and Waples [61,62]
Abu Hammad-1	2550 m (Khataba Fm)	0.62	Early oil generation
	3450 m (Bir Maghara Fm)	0.80	Peak oil generation
	4250 m (Rajabiah Fm)	1.00	onset gas generation
Kabrit-1	2900 m (Rajabiah Fm)	0.64	Early oil generation

The above organic geochemical results coincide well with our assessment.

The results of the Jurassic-Lower Cretaceous palynofacies, kerogen type distribution and thermal maturation indicate possible horizons of source rocks which could generate large quantities of hydrocarbons (Figs. 6-8). This may increase the chances of discovering an oil field in the northern part of the Eastern Desert:

1. Highly oil-prone and mature amorphous source rocks are applied to the shales of the lower Masajid, Khatatba (Bathonian coal of Safa Member, [29]) and middle Rajabiah formations in the Abu Hammad-1 well.

2. Highly oil-prone but immature amorphous source rocks are attributed to the Alamein and Alam El Bueib formetions in the Abu Hammad-1 well, and the upper Masajid Formation in the Kabrit-1 well.

3. Oil-prone, mature source rocks can be distinguished in the upper Masajid Formation in the Abu Hammad-1

well, Rajabiah Formation in Kabrit-1 well, middle Khatatba, and Shusha formations in Q-71-IX well.

4. Gas-prone, mature source rocks are detected in the upper Rajabiah Formation in the Abu Hammad-1 well, Bir Maghara Formation in Kabrit-1, lower Khatatba, Bir Maghara and Rajabiah formations in Q-71-IX well.
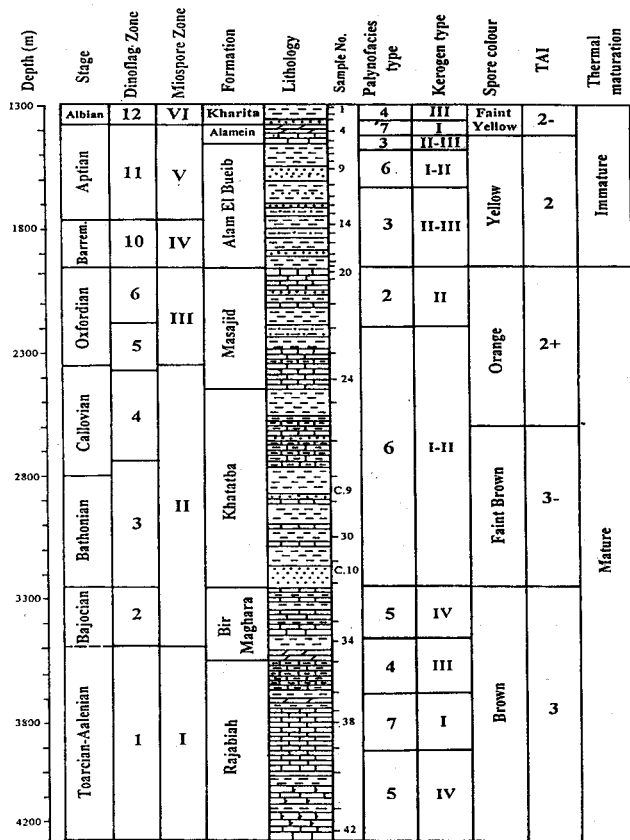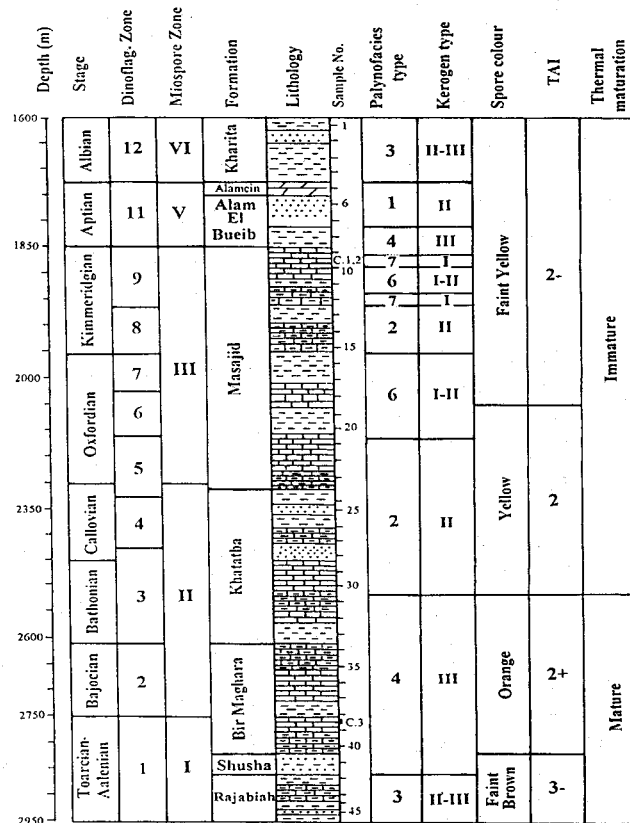
Fig. 6 : Summary of the proposed palynofacies, kerogen type, spore colour, thermal alteration index (TAI) and the corresponding thermal maturation in the Jurassic to Lower Cretaceous of the Abu Hammad-1 well.

Fig. 8 : Summary of the proposed palynofacies, kerogen type, spore colour, thermal alteration index (TAI) and the corresponding thermal maturation in the Jurassic of the Q-71-IX well.

Fig. 7 : Summary of the proposed palynofacies, kerogen type, spore colour, thermal alteration index (TAI) and the corresponding thermal maturation in the Jurassic to Lower Cretaceous of the Kabrit-1 well.
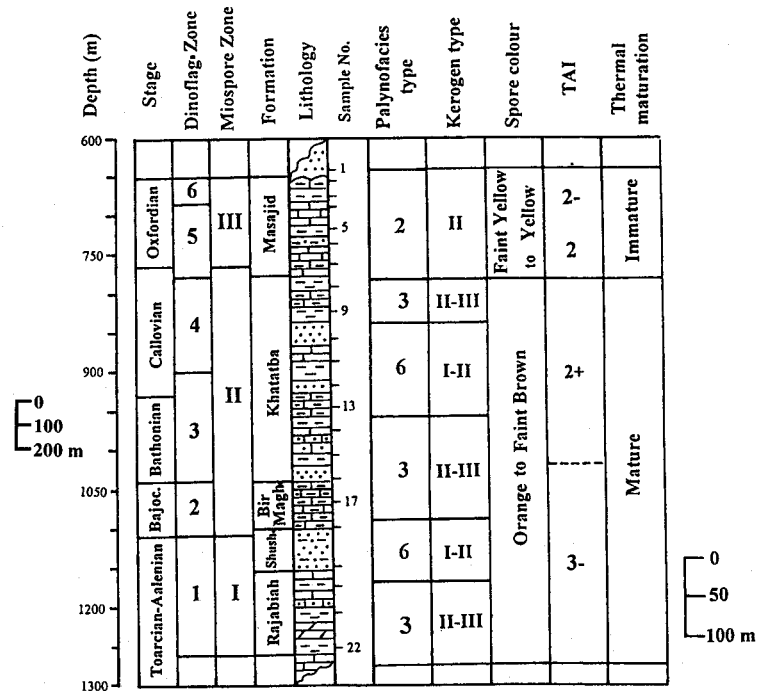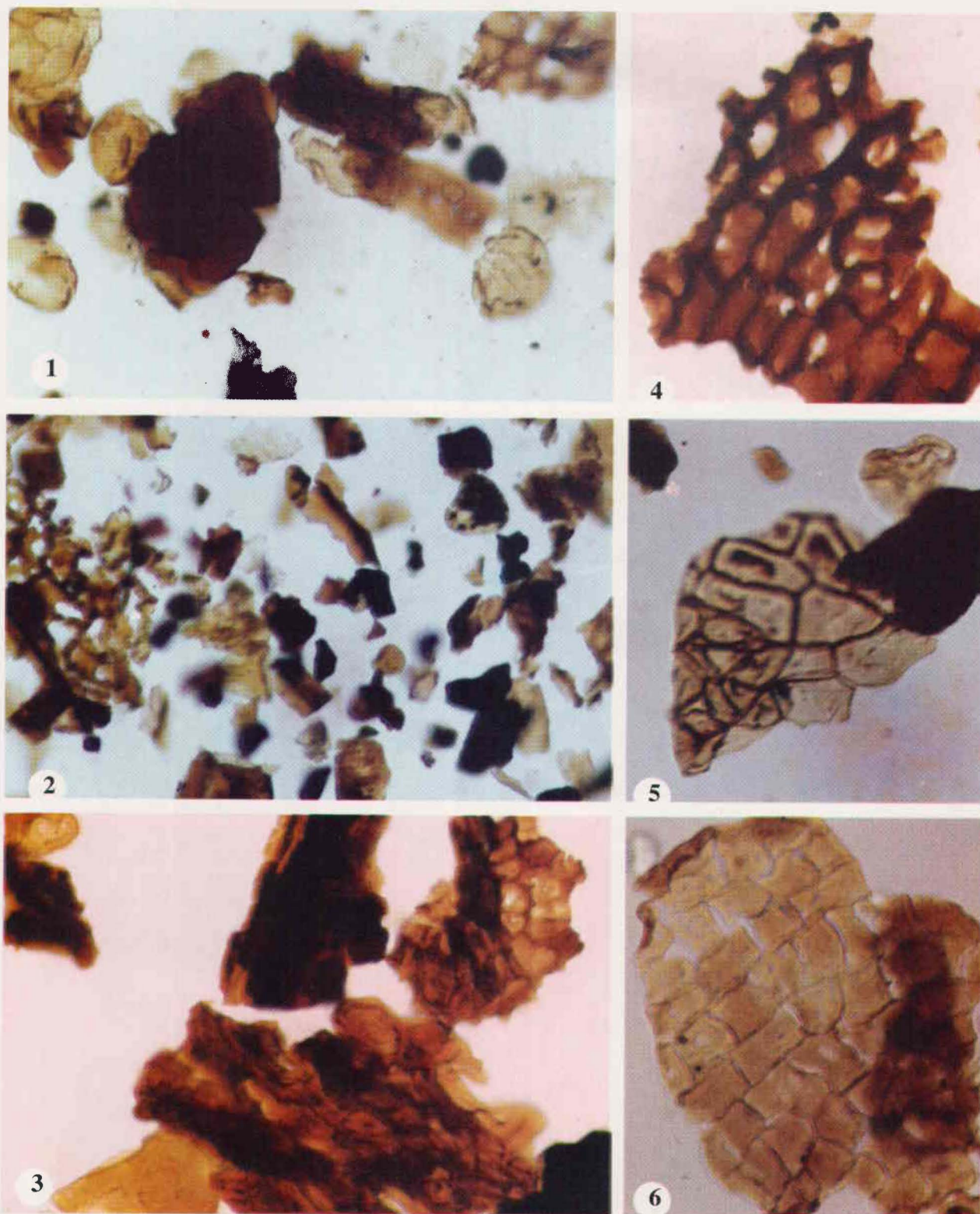
PLATE 1 :-

1. Palynofacies 2, x 250 : Dominated by dinoflagellate cysts and microforaminiferal linings (Kabrit-1, 2011 m).

2. Palynofacies 3, x 250 : Phytoclasts and palynomorphs, phytoclasts composed mainly of cuticles and tracheid wood fragments (Abu Hammad-1, 1860 m).

3. Palynofacies 3, x 400: Enlarged phytoclasts and part of multicellular fungal "Fruiting body" in the top right corner (Q-71-IX, 792 m).

4, 5 & 6. Dispersed cuticle fragments with guard cells. Cells are regular rectangular to polygonal in outlines (probably gymnosperm in origin), x 400 (4. Q-71-IX, 975 m; 5. Kabrit-1, 2408 m;6. Q-71-IX, 792 m).
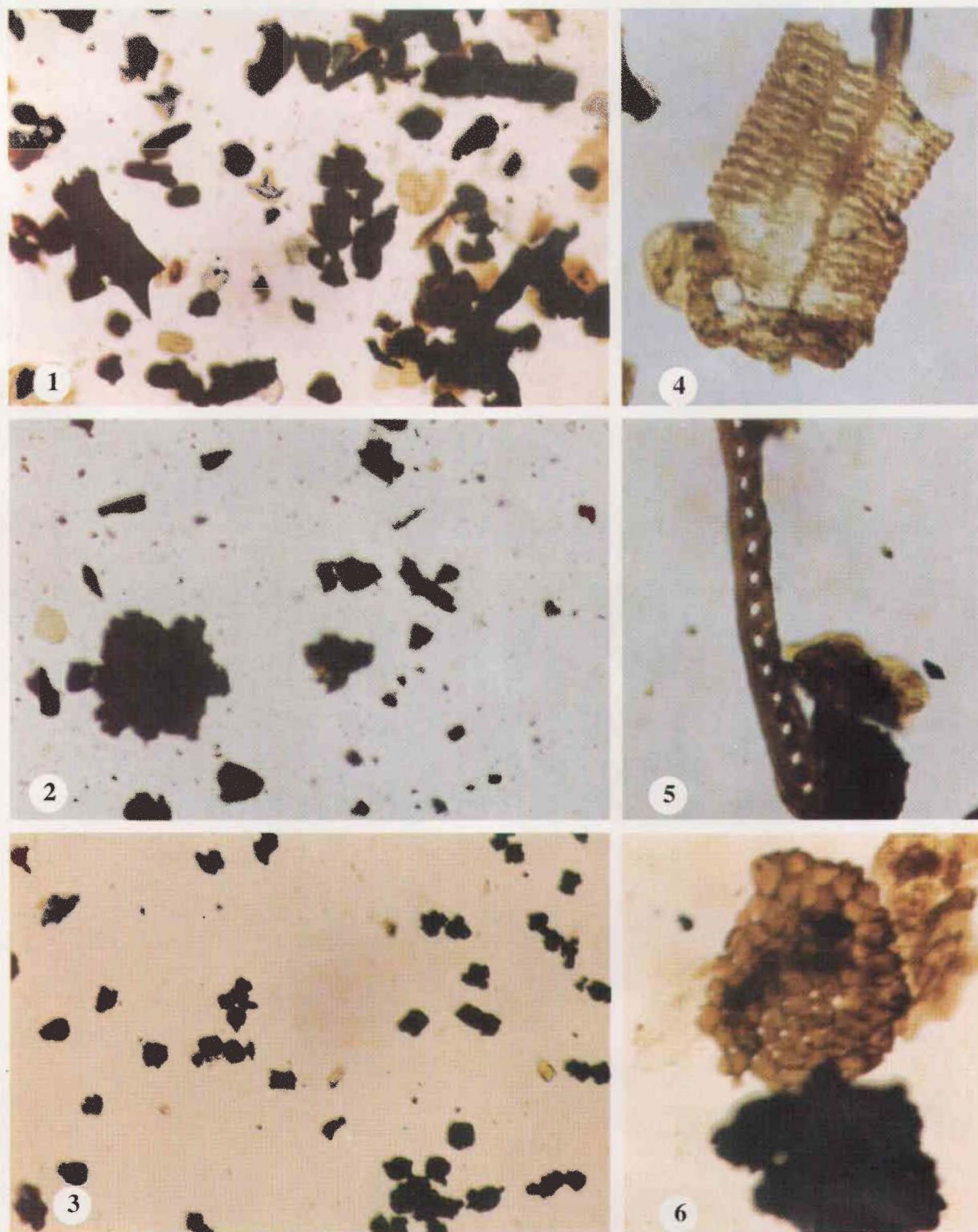
PLATE 2 :-

1. Palynofacies 4, x 250: Opaque terrestrial fragments with abundant palynomorphs (Abu Hammad- 3552 m).
2. Palynofacies 5, x 400: Opaque terrestrial fragment with AOM. Also framboidal pyrite is frequent (Abu Hammad-1, 4152 m).
3. Palynofacies 5, x 250: Opaques with abundant framboidal pyrite (Abu Hammad-1, 3399 m).
4. Spiral vessels derived from the xylem, or water conducting tissue of the plant, x 400 (Q-71-IX, 792 m).
5. Biostructured phytoclast of gymnospermous tracheid fragment with conspicuous uniserial perforated bordered pits., x 400 (Kabrit-1, 2469 m).
6. Part of fungal "fruiting body" above opaque. The relative dark brown colour indicates melanization as a result of exposure to atmospheric oxygen and a terrestrial origin, x 630 (Q-71-IX, 640 m).
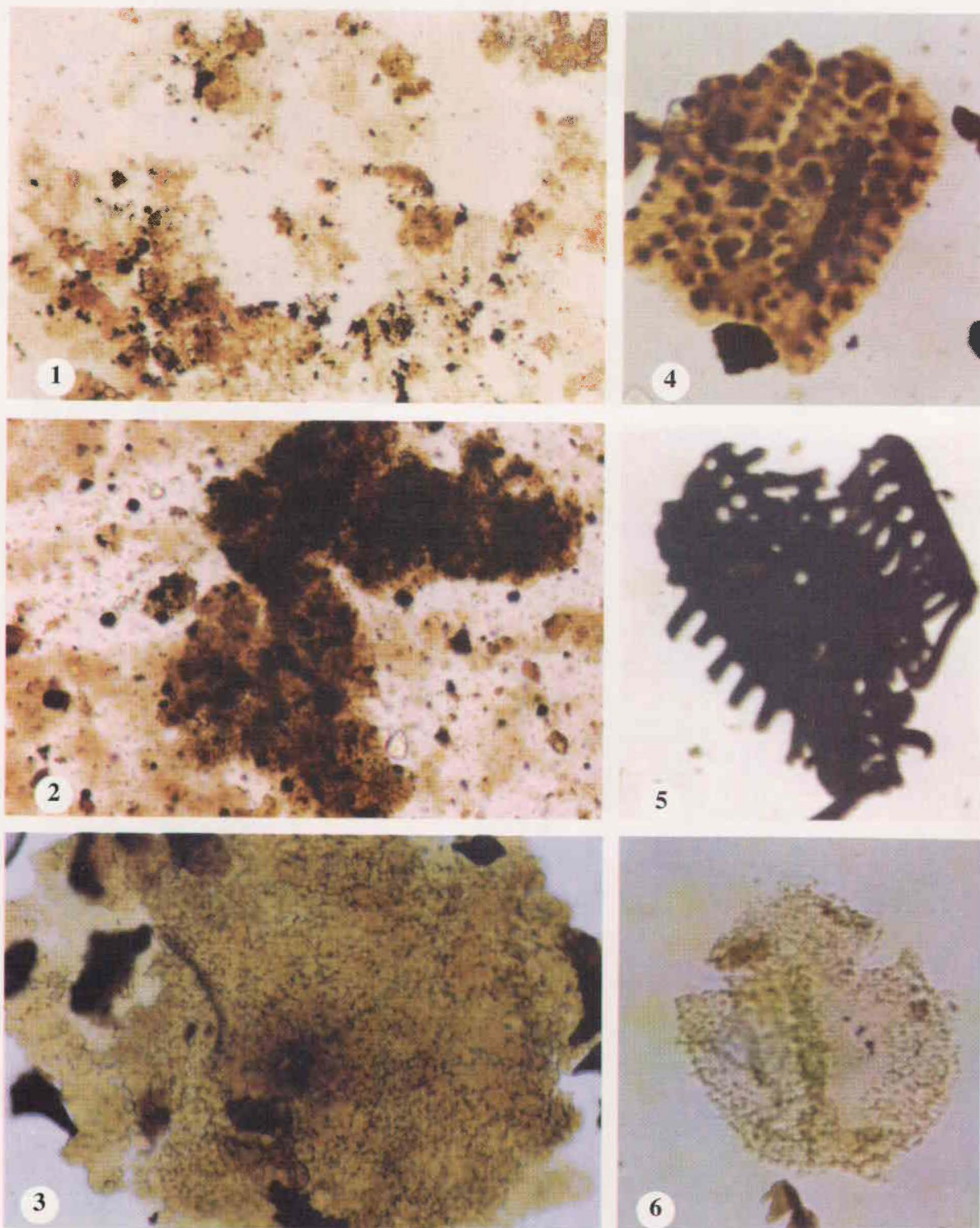
PLATE 3 :-

1. Palynofacies 6, x 250: AOM with palynomorphs (dinoflagellatecysts and microforaminiferal linings) (Kabrit-1, 1920 m).
2. Palynofacies 7, x 250: Granular variety of AOM which consists of irregular brown granules in an amorphous matrix (Kabrit-1, Core 1& 2 , 1880 m).
3. Large ?Resin particle with imbeded spores, opaques and phytoclasts, x 250 (Abu Hammad-1, 1950 m).
4. Dispersed cuticle fragment , x 400 (Kabrit-1, 1676 m).
5. Opaque biostructured phytoclast. The clear scalariform pitting shows that the particle is derived from tracheid tissue, and the fine preservation of the microstructure suggests a charcoal origin, x 630 (Abu Hammad-1, 3399 m).
6. Marine dinoflagellate cyst, Tenua hystrix Eisenack , x 630 (Kabrit-1, 1707 m).
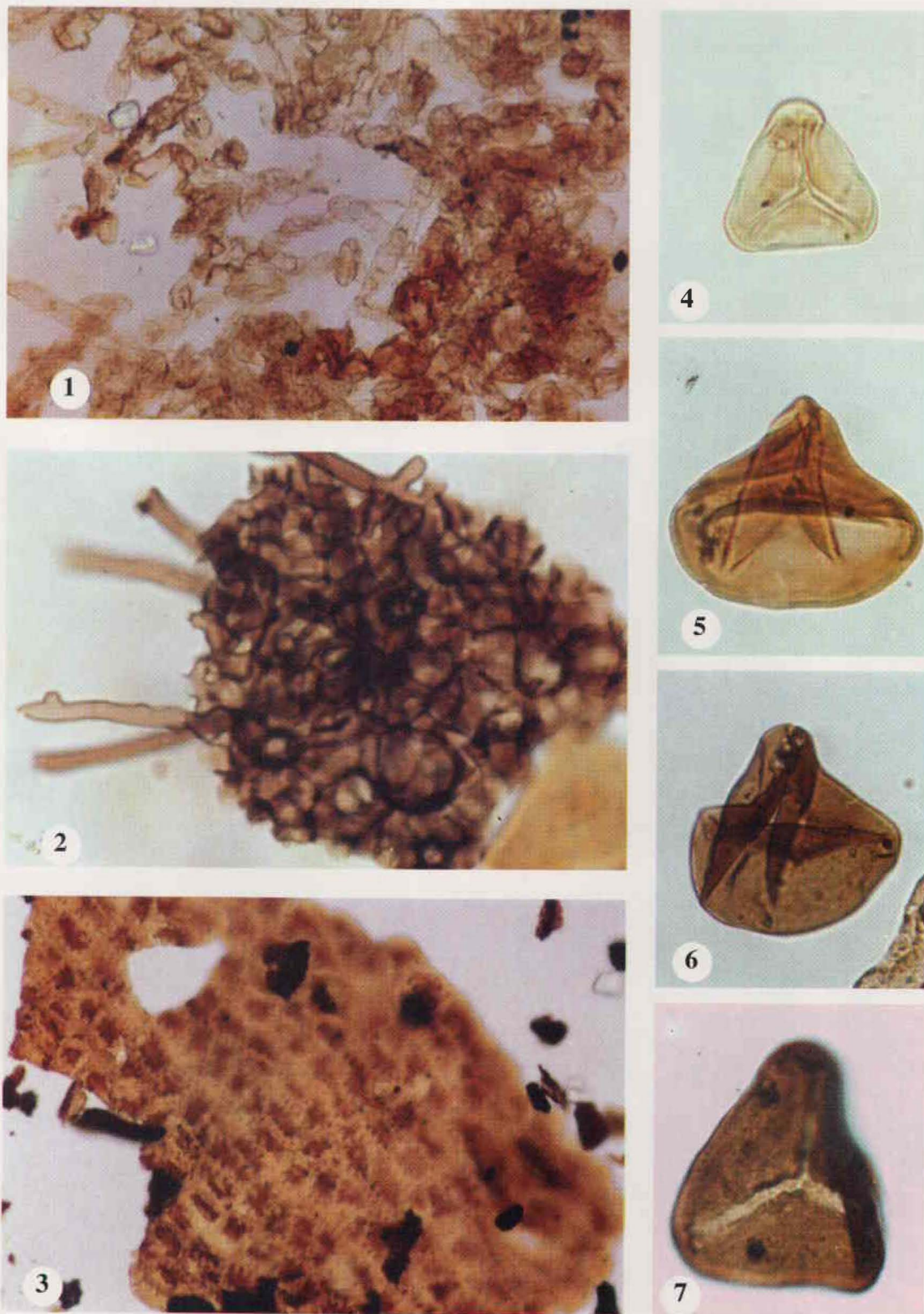
PLATE 4 :-

1. Algal agglomeration, x 400 (Q-71-IX, 945 m).
2. Tangled mass of melanized fungal hyphae, x 1000 (Q-71-IX, 823 m).
3. Dispersed cuticle phytoclast. The orange-brown areas within the cell outlines probably represent residual phyllovitrinite (corpocollinite) material produced during the degradation of the mesophyll tissue, prior to final separation of the cuticle, x 250 (Kabrit-1, 1615 m).

Spore colour and TAI (according to Pearson, 1990)

4. *Gleicheniidites* sp., TAI= 2- to 2, Kabrit-1, 2134 m, slide A, coord. 16.5/104 (H43/4).
5. *Dictyophyllidites* sp., TAI= 2+, Q-71-IX, 836 m, slide A, coord. 19/113.5 (G53/2).
6. *Deltoidospora* sp., TAI= 3-, Kabrit-1, 2835 m, slide A, coord. 21/100 (D39/2).
7. *Cf. Matonisporites* sp., TAI= 3, Abu Hammad-1, 3552 m, slide A, coord. 18.5/117 (G56/2).

Acknowledgement

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