Jurassic–Cretaceous palynomorphs, palynofacies, and petroleum potential of the Sharib-1X and Ghoroud-1X wells, north Western Desert, Egypt

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ABSTRACT

Palynomorph and palynofacies analyses have been performed on 93 cuttings samples from the Jurassic Masajid Formation and Cretaceous Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations in the Sharib-1X and Ghoroud-1X wells, north Western Desert, Egypt. Two palynological biozones are proposed for the studied interval of the Sharib-1X well: the *Systematophora penicillata*–*Escharisphaeridia pocockii* Assemblage Zone (Middle to Late Jurassic) and the *Cretacaeiporites densimurus*–*Elateroplicites africaensis*–*Reyrea polymorpha* Assemblage Zone (mid-Cretaceous: late Albian to early Cenomanian). Spore coloration and visual kerogen analysis are used to assess the thermal maturation and source rock potential. Mature oil prone to overmature gas prone source rocks occur inthe studied interval of the Sharib-1X well, whereas highly mature to overmature gas prone source rocks occur in the studied interval of the Ghoroud-1X well.

Palynofacies and palynomorph assemblages in both wells reflect shallow marine conditions throughout the Jurassic and the late Albian and early Cenomanian. During these times, warm and dry climatic conditions prevailed. The Cretaceous palynomorph assemblages of the Sharib-IX well correlate with the Albian-Cenomanian Elaterates Province of Herngreen et al. (1996).

**Keywords:** Jurassic; Cretaceous; palynomorphs; palynofacies; thermal maturation; petroleum potential

**1. Introduction**

Since the 1960s, Egyptian researchers have concentrated on the classical taxonomic, palynostratigraphic and paleoenvironmental aspects of palynology in their studies. Only during the past 15 years they started to payattention to the more applied sides such as organic thermal maturity and source rock potential (e.g. Ibrahim, 1996, 2002a; Ibrahim et al., 1997). This trend has even increased in the past five years with the recent and ongoing work of El Beialy et al. (2008, 2010) and Zobaa et al. (2008, 2011) which integrated other tools such as stable isotope and organic geochemical analyses. The present study continues this trend by focusing on the hydrocarbon potential of the subsurface Jurassic and Cretaceous sequence in the north Western Desert of Egypt, where there are many oil discoveries (Schlumberger, 1995).

Two wells located in the north Western Desert of Egypt, the Sharib-1X (30°11’36” N, 28°19’06” E) and Ghoroud-1X (30°03’08” N, 28°19’15” E) (Fig. 1), were studied. Although the Sharib-1X well reached a total depth of 8205 ft (2501 m; WEPCO, 1971), our palynological investigation was restricted to the 6160–5360 ft (1878–1634 m) interval. Omran et al. (1990) studied five samples from the Sharib-1X well, three of which were from an interval older than that of our study. These authors focused on palynostratigraphic and paleoenvironmental implications, and did not attempt to characterize the kerogen contents of their samples. The Ghoroud-1X well reached a total depth of 10,384 ft (3165 m; WEPCO, 1970) and our investigation was restricted to the 9810–6440 ft (2990–1963 m) interval. This interval was also studied by Mahmoud and Moawad (1999) who recognized two informal palynomorph zones of Albian and early Cenomanian age and discussed the paleoenvironmental conditions. They did not present any palynofacies data in their study which is augmented in the present study.

The objectives of the present study for both wells were to: 1) identify the palynofacies types and determine possible source rock horizons, 2) use spore coloration to evaluate the thermal maturity of the samples studied, and 3) provide insights into the depositional paleoenvironments. In addition, the Sharib-1X well was studied to establish biostratigraphic zonations.

**2. Material and methods**

The present study is based on 66 cuttings samples from the Sharib-1X well and 27 cuttings samples from the Ghoroud-1X well in the Egyptian north Western Desert. The samples were prepared using standard maceration techniques that included demineralizing the samples with HCl and HF, and sieving the residue at 125 µm and 10 µm. The residues were not oxidized or stained since this would have hindered the study of kerogen particles and spore coloration. Prepared slides were examined under transmitted light microscopy at variable magnifications to generate qualitative and semi-quantitative data for the particulate organic matter (POM). A total of 200 palynomorph specimens and 200 kerogen particles were counted for palynostratigraphic and palynofacies studies, respectively. All slides and residues are stored and catalogued in the Paleontology Research Laboratory, Geology Department, Faculty of Science, Benha University, Egypt.

**3. Lithostratigraphy**

The studied intervals in the Sharib-1X and Ghoroud-1X wells represent the Jurassic Masajid Formation and Cretaceous Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations (Figs. 2, 3). The lithologies, unit thicknesses, and tops of these formations are discussed below, following WEPCO (1970, 1971) and Schlumberger (1995). It is evident that the Masajid Formation is missing from the Ghoroud-1X well, whereas the Alam El Bueib, Alamein and Dahab formations are absent in the Sharib-1X well.

*3.1. Jurassic*

The Jurassic is represented only by the Masajid Formation in our study. Its type section as defined by Al Far (1966) is located at Gebel Maghara in the Egyptian Sinai Peninsula where it is 1886 ft (575 m) thick and is composed mainly of coralline limestone with clay and sandstone beds. Keeley et al. (1990) redefined the Masajid Formation as a more carbonate-dominated interval. In the present study, the Masajid Formation consists mainly of medium to hard dolomite with shale interbeds, changing downsection to alternating beds of cryptocrystalline medium to hard sandy to silty limestone, white calcareous sandstone and brown fissile calcareous shales. It occurs at the base of the studied interval in the Sharib-1X well, where it unconformably underlies the Kharita Formation (Fig. 2). The studied interval of the Masajid Formation in this well is 205 ft (62 m) thick, and occurs at a depth of 6171–5966 ft (1881–1818 m).

*3.2. Cretaceous*

The subsurface Cretaceous in the Western Desert is separated from the underlying carbonate Masajid Formation by a major regional unconformity. The Cretaceous deposits comprise mainly fine- to coarse-grained clastics, and are subdivided from base to top into the Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations (Schlumberger, 1995).

*3.2.1. Alam El Bueib Formation*

The main constituents are friable fine- to medium-grained sandstone with dark gray to brownish gray silty shale interbeds (Fig. 3). The examined interval is 1827 ft (557 m) thick in the Ghoroud-1X well, occurring at a depth of 9850–8023 ft (3002–2445 m).

*3.2.2. Alamein Formation*

This consists mainly of hard dense brown dolomite with a few thin shale interbeds at the base and top (Fig. 3). It has a thickness of 188 ft (57 m) in the Ghoroud-1X well, occurring at a depth of 8023–7835 ft (2445–2388 m).

*3.2.3. Dahab Formation*

Shale with minor limestone interbeds are mainly represented (Fig. 3). This unit has a thickness of 15 ft (4.5 m) in the Ghoroud-1X well and occurs at a depth of 7835–7820 ft (2388–2384 m).

*3.2.4. Kharita Formation*

This is represented by coarse-grained slightly calcareous (at base) sandstone of varying color with greenish to dark gray fissile calcareous shale interbeds in the Sharib-1X well (Fig. 2). In the Ghoroud-1X well it consists of quartzitic fine- to medium-grained anhydritic sandstone at the top and occasionally fine- to coarse-grained sandstone with calcareous or anhydritic matter associated with dark gray micaceous shale interbeds at base (Fig. 3). It rests unconformably above the Masajid Formation in the Sharib-1X well and conformably above the Dahab Formation in the Ghoroud-1X well. In the Sharib-1X well, the Kharita Formation attains a thickness of 539 ft (164 m) and occurs at a depth of 5966–5427 ft (1818–1654 m), whereas in the Ghoroud-1X well it is 705 ft thick (215 m) at a depth of 7820–7115 ft (2384–2169 m).

*3.2.5. Bahariya Formation*

This formation was defined by Said (1962) and El Akkad and Issawi (1963). Its type section is 567 ft (173 m) thick, and is located at Gebel El Dist in the Bahariya Oasis, Western Desert. TheBahariya Formation comprises medium- to coarse-grained sandstone with calcareous silty shale interbeds in the Sharib-1X well (Fig. 2). In the Ghoroud-1X well it is composed of well-sorted calcareous sandstones of varying color with greenish-gray to dark-gray slightly calcareous fissile shale interbeds (Fig. 3). It conformably overlies the Kharita Formation in both wells. The studied interval in the Sharib-1X well is 127 ft (39 m) thick and occurs at a depth of 5427–5300 ft (1654–1615 m), whereas in the Ghoroud-1X, well the studied interval attains a thickness of 715 ft (218 m) at a depth of 7115–6400 ft (2169–1951 m).

**4. Palynostratigraphy**

Two palynological biozones (hereinafter palynozones) are defined for the studied interval in the Sharib-1X well and correlated with selected contemporaneous palynozonations identified in Egypt and other northern Gondwana regions. Pollen and spores are stratigraphically important in the present study because of their abundance, favorable preservation, high diversity and continuous vertical distribution. They are particularly useful in Albian and Cenomanian biozonations of the Egyptian north Western Desert. Dinoflagellate cyst taxa are less important due to their scarcity and poor preservation but provide useful independent evidence for age dating. Two palynozones are proposed based on both the occurrences and abundances of palynomorph taxa. They are discussed in ascending stratigraphic order. Plates I, II, and III illustrate several diagnostic taxa for the described palynozones.

*4.1. Palynozone I: Systematophora penicillata*–*Escharisphaeridia pocockii* *Assemblage Zone* *(Middle to Late Jurassic)*

*Definition:* From the base of the studied section to the highest occurrence of the dinoflagellate cysts *Systematophora penicillata* and *Escharisphaeridia pocockii*, and the acritarch *Micrhystridium lymensis*.

*Occurrence:* Sharib-1X, depth interval 6171–5966 ft (1881–1818 m), thickness 205 ft (62 m), samples 66–55, comprising the entire studied interval of the Masajid Formation.

*General characteristics:* Common to highly abundant spores and gymnosperm pollen such as *Concavisporites* sp., *Dictyophyllidites harrisii*, *Gleicheniidites senonicus*, *Triplanosporites* sp., *Deltoidospora* spp., *Araucariacites australis*, *Classopollis* spp., *Circulina parva*, and *Spheripollenites psilatus*. Angiosperm pollen are absent and very few dinoflagellate cysts are present (see Fig. 6).

*Age:* The abundant pollen and spore taxa present in this palynozone are generally long ranging and have been recorded previously in Jurassic and Cretaceous sequences in Egypt and elsewhere (e.g. Kora and El Beialy, 1989; El-Sheikh and Aly, 1994; Ibrahim and Schrank, 1996; Schrank and Mahmoud, 1998; El Beialy et al., 2002a, b; Mahmoud and Schrank, 2003). This hinders their use in assigning a precise age for this zone. However, the presence of the key Jurassic dinoflagellate cyst species *Adnatosphaeridium caulleryi*, *Ctenidodinium combazii*, *Escharisphaeridia pocockii*, *Sentusidinium rioultii* and *Systematophora penicillata*, and the acritarch *Micrhystridium lymensis* precludes a Cretaceous age for this assemblage. These species have been recorded previously from the Middle and Upper Jurassic of Egypt, other African countries, and worldwide (e.g. Ibrahim and Schrank, 1996; Poulsen, 1996; Aboul Ela and El Shamma, 1997; El Beialy and Ibrahim, 1997; Mahmoud and Moawad, 2000; Abdel Mohsen et al., 2001; Ibrahim et al., 2002). In particular, *Ctenidodinium combazii* has an age range of upper Bajocian through lower Callovian in northern mid-latitudes (Brinkhuis et al., 2006).

The Masajid Formation has been dated previously as Middle to Late Jurassic (e.g. Omran et al., 1989; El Beialy et al., 1990; Ibrahim and Schrank, 1996; Mahmoud et al., 1999; Mahmoud and Moawad, 2000; Ibrahim et al., 2001, 2002). Its base occurs within the Callovian (e.g. Keeley et al. 1990, Abdel-Kireem et al., 1996; Ibrahim et al., 1997) and its top extends locally into the Tithonian (e.g. Keeley et al. 1990). The present study supports a Middle to Late Jurassic age, and the presence of *Ctenidodinium combazii* suggests an age no younger than Callovian.

*Correlation:* Palynozone I can be correlated with other previously established Egyptian zonations; For example, it correlates with the Kimmeridgian Zone I of Ibrahim and Schrank (1996) based on its miospore content, but differs in its microplankton composition. The Upper Jurassic Assemblage Zone I of Mahmoud et al. (1999) is similar because of the dominance of pteridophytic spores and gymnosperm pollen grains. The Toarcian?–Aalenian *Classopollis/Circulina*–*Deltoidospora* spp. Assemblage Zone of Ibrahim et al. (2001) is also comparable with the present assemblage. In northeast Libya, the Middle Jurassic (Callovian) *Energlynia acollaris* Assemblage Zone of Thusu et al. (1988) is comparable due to the presence of both *Adnatosphaeridium caulleryi* and *Systematophora penicillata*.

*4.2. Palynozone II: Cretacaeiporites densimurus–Elateroplicites africaensis–Reyrea polymorpha Assemblage Zone (late Albian to early Cenomanian)*

*Definition:*From the highest occurrence of the Jurassic dinoflagellate cysts of Palynozone I to the top of the studied section in the Sharib-IX well.

*Occurrence:* Sharib-1X, depth interval 5966–5360 ft (1818–1634 m), thickness 606 ft (185 m), samples 52–1, representing the Kharita and Bahariya formations.

*General characteristics:* Very high abundances of the well-known angiosperm pollen species *Afropollis jardinus* (up to ~30–45% of the total palynomorph count). Abundant to common *Afropollis kahramanensis*, *Crybelosporites pannuceus*, *Elaterosporites klaszii* and *Pennipollis reticulatus*. Presence of *Cretacaeiporites densimurus*, *Elaterocolpites castelainii*, *Elateroplicites africaensis, Galeacorna causea*, *Retimonocolpites variplicatus, Reyrea polymorpha* and *Sofrepites legouxae*. *Xiphophoridium alatum* is among the 18 dinoflagellate cyst taxa present. All recorded palynomorphs, including dinoflagellate cysts, are shown in Fig. 6.

*Age:* This palynozone contains important markers present in the mid-Cretaceous Albian–Cenomanian Elaterates Province of Herngreen et al. (1996), which are commonly used as Albian–Cenomanian indicators in Africa and worldwide.

*Cretacaeiporites densimurus* and *Elateroplicites africaensis* do not appear before the late Albian in Africa in general and Egypt and Sudan in particular (e.g. Schrank, 1990; Schrank and Ibrahim, 1995; Mahmoud and Moawad, 2000; Schrank, 2001) (Fig. 4). Therefore, t heir presence suggests an age not older than late Albian for this palynozone.

*Reyrea polymorpha* is a palynomorph of unknown affinity that was first described in the lower to middle Albian of Brazil by Herngreen (1973). In Africa it has been recorded in sequences ranging in age from late Barremian to early Cenomanian (e.g. Thusu and van der Eem, 1985; Lawal and Moullade, 1986; Sultan, 1987; El-Shamma, 1988; El-Shamma and Arafa, 1988; Penny, 1988; El Beialy, 1993a; Ibrahim, 1996; Mahmoud and Moawad, 1999; Ibrahim et al., 2001; Ibrahim, 2002b) (Fig. 4). Thus, *Reyrea polymorpha* suggests that this palynozone is not younger than early Cenomanian.

The dinoflagellate cyst *Xiphophoridium* *alatum* has a basal range of 104 Ma (upper Albian) in equatorial latitudes, and 107 Ma (mid-Albian) in northern mid-latitudes (Brinkhuis et al., 2006). This supports an age not older than late Albian for this palynozone.

Based on the co-occurrence of *Cretacaeiporites densimurus*, *Elateroplicites africaensis* and *Reyrea polymorpha*, Palynozone II is late Albian to early Cenomanian in age.

*Correlation:*Palynozone II appears to correlate with numerous published Egyptian Albian and Cenomanian palynozones. (Fig. 5). They include: 1) the late Albian–early Cenomanian Assemblage Zone II of Sultan and Aly (1986); 2) the *Cretacaeiporites scabratus* Assemblage Zone of El Beialy (1994a); 3) the late Albian–early Cenomanian Zone PIV of Mahmoud and Moawad (2000); 4) the Albian–early Cenomanian? Assemblage Zone III of Soliman et al. (1991); 5) the early Albian Assemblage Zone-IV of El-Shaarawy et al. (1992); 6) the early and middle Cenomanian Zone V (*Classopollis brasiliensis*–*Elaterocolpites castelainii*–*Cretacaeiporites densimurus* Assemblage Zone) of Schrank and Ibrahim (1995); 7) the Albian Assemblage Zone IV of Mahmoud et al. (1999); 8) the early Cenomanian Zone C (*Elaterosporites klaszii* Zone) of Aboul Ela et al. (1996); 9) Palynomorph zone no. II of Mahmoud and Moawad (1999); and 10) Zone PS-III of Mahmoud and Moawad (2002).

Palynozone II is remarkably similar on the basis of its sporomorph assemblage to the Vraconian–early Cenomanian IVB Association erected for Libyan sedimentary rocks by Uwins and Batten (1988). This palynozone can also be correlated with those identified for rock successions in the Sudan. Except for the absence of elaterate marker species, majority of the taxa in Palynozone II were used by Awad (1994) to establish the late Albian–late Cenomanian S-IV Assemblage Zone. The elaterates may be missing due to ecological factors. Still in the Sudan, Schrank (1994) established late Albian–early Cenomanian Elaterate–*Araucariacites*–*Leptolepidites* Assemblage Zone in northern Kordofan to the west of Khartoum. This assemblage is comparable to Palynozone II. In other African countries, sporomorph associations closely resembling Palynozone II include sequence VIII from the upper Albian–lower Cenomanian deposits of Senegal and the Ivory Coast in West Africa described by Jardiné and Magloire (1965) and Jardiné (1967), and associations described for Albian deposits of the Algero–Tunisian Sahara reported by Reyre (1966, 1973).

Palynozone II is comparable to palynomorphs associations described for sedimentary sequences in Qatar. These are the upper Albian–lower Cenomanian palynologic association from basal Unit A of the Ahmadi Formation (El Beialy and Al Hitmi, 1994) and the middle–upper Albian Nahr Umr Formation (Ibrahim et al., 2000). A similar sporomorph association in Brazil, the upper Albian–lower Cenomanian pollen zone II of

Herngreen (1973) is also comparable to those encountered from Palynozone II.

**5. Palynofacies analysis, organic thermal maturation, and source rock evaluation**

Four main constituents of kerogen have been recognized using the classification scheme of Tyson (1993, 1995). **Palynomorphs** refer to all discrete HCl- and HF-resistant organic-walled microfossils. **Phytoclasts** are all structured, yellow to brown, dispersed silt- to fine sand-sized particles of plant-derived kerogen other than palynomorphs. **Opaques** include all structured brownish-black to black oxidized or carbonized particles of plant-derived kerogen. **Amorphous organic matter** (AOM) refers to all structureless dispersed silt- to fine sand- sized particles of kerogen, whether of marine or non-marine origin.

*5.1. Palynofacies assemblages*

*5.1.1. Sharib-1X Well*

The interval from 6160 to 5360 ft (1878–1634 m) in the Sharib-1X well can be classified into three palynofacies assemblages based on the proportions of the POM groups. These palynofacies assemblages, from oldest to youngest, are described below.

*5.1.1.1. Palynofacies 1 (opaque dominant)*

Palynofacies 1 occurs from 6160 to 6020 ft (1878–1835 m) in the Masajid Formation (Fig. 2). It is characterized by abundant opaques, frequent phytoclasts and AOM and common palynomorphs (mainly terrestrial) (Fig. 7).

The opaques are dark brown to black in color, and composed of well-preserved equant to lath-shaped fragments of varying sizes. Some particles have a pitted structure indicating that they are derived from tracheid tissue. The phytoclasts and AOM are medium to dark brown and are similar in form to those described for Palynofacies 2 and 3. Palynomorphs are generally medium to dark brown in color.

This facies is identified as Type III/IV kerogen based on the moderate percentages of phytoclasts and dominance of opaques.

*5.1.1.2. Palynofacies 2 (AOM and phytoclast dominant)*

Palynofacies 2 straddles the uppermost Masajid Formation and lower Kharita Formation, between 6020 and 5700 ft (1835–1737 m) (Fig. 2). It is characterized by abundant AOM, frequent phytoclasts, common opaques and rare terrestrial palynomorphs (Fig. 7).

The amorphous organic matter present consists mainly of well-preserved pale yellow to orange particles. Most of the recorded fragments show diffuse edges but granular forms are also present in small amounts. The phytoclasts are brown in color and similar in form to that described from Palynofacies 1. The opaques are dark brown to black equant and lath-shaped. The palynomorphs are mainly orange to medium brown.

This facies is tentatively classified as Type II kerogen based on the dominance of pale yellow to orange AOM. Although the AOM is assumed to be of marine origin, it has not been confirmed by fluorescence microscopy.

*5.1.1.3. Palynofacies 3 (phytoclast and opaque dominant)*

This is the youngest of the three palynofacies, which occurs between 5700 and 5360 ft (1737–1634 m) in the upper part of the Kharita Formation and the Bahariya Formation (Fig. 2). It is characterized by abundant phytoclasts, frequent opaques, common AOM and common to rare palynomorphs (Fig. 7).

The phytoclasts consist mainly of pale brown, moderately- to well-preserved structured plant fragments. Tracheids are the most common phytoclast constituent and they are mostly in the form of elongate lath-shaped particles. Cuticles have regular rectangular cell outlines, which may be indicative of a gymnospermous origin (Tyson, 1995). They are dark brownish in color. Xylem ray tissues with their characteristic cross-hatched structure are rarely represented. The opaques are equant to lath-shaped fragments. The AOM is mostly diffuse-edged and orange to brown in color. The palynomorphs are yellow to yellowish orange and mainly of terrestrial origin.

This facies represents Type III kerogen based on the dominance of pale brown phytoclasts.

*5.1.2. Ghoroud-1X Well*

Only one palynofacies assemblage is present in the 9810–6440 ft (2990–1963 m) interval (Fig. 3).

*5.1.2.1. Palynofacies 1 (phytoclast and opaque dominant)*

Palynofacies 1 is characterized by abundant opaques and phytoclasts, common palynomorphs (generally terrestrial) and rare amorphous organic matter (Fig. 8).

Opaques and phytoclasts differ only in their larger sizes from those described in the Sharib-IX well. Palynomorphs are dominated by terrestrial taxa with medium to dark brown color. The AOM is mostly granular and medium to dark brown.

This palynofacies is considered to be of Type III/IV kerogen based on the dominance of medium to dark brown phytoclasts.

*5.2. Organic thermal maturation*

The color of simple thin-walled psilate spores (e.g. *Deltoidospora*, *Dictyophyllidites*, *Triplanosporites*) was used to determine the organic thermal maturation for both the Sharib-IX and Ghoroud-IX wells. Colors were compared with Batten’s (1980) scale of palynomorph colors and Pearson’s (1984) color chart to determine the numerical thermal alteration index (TAI) of samples. Equivalent vitrinite reflectance (Ro%) values were obtained using the correlation chart of Traverse (2007 fig. 19.2, p. 584) (Figs. 2, 3).

*5.2.1. Sharib-1X Well*

The succession studied in the Sharib-1X well generally shows a marked increase in color intensity with increasing depth. In slides that exhibited variation in color rank, the mean was used. TAI values range from 4-, 3+, 3, 3-, 2+, 2, to 2- and correspond to between 2.0 and 0.3% vitrinite reflectance (Fig. 2). Organic maturity for each of the three palynofacies assemblages is discussed below.

*Palynofacies 1:* Contains highly mature to overmature palynomorphs with medium to dark brown color corresponding to 4- to 3+ TAI and an estimated vitrinite reflectance of 2.0–1.2%.

*Palynofacies 2:* Dominated by mature, orange and light to medium brown palynomorphs. This indicates a decrease in TAI values from 3, 3-, to 2+. The corresponding vitrinite reflectance value is 1.1–0.5%.

*Palynofacies 3:* Characterized by immature palynomorphs with yellow to yellowish orange color corresponding to 2 to 2- TAI. This corresponds to 0.5–0.3% vitrinite reflectance.

*5.2.2. Ghoroud-1X Well*

The studied succession in this well is characterized by generally highly mature to overmature palynomorphs of medium to dark brown color. This reflects 4- to 3+ TAI which corresponds to an estimated vitrinite reflectance of 2.0–1.2% (Fig. 3).

*5.3. Source rock potential*

Source rock potential has been identified on the basis of palynofacies analysis to assess whether the kerogen is oil or gas prone, and spore coloration to determine levels of thermal maturation. Total organic carbon values are not yet available for these wells, although they clearly will be important for confirming the source potential of these rocks. Meanwhile, the following intervals are provisionally identified.

In the Sharib-IX well, the lower part of the Masajid Formation corresponding to Palynofacies 1 contains highly mature to overmature gas prone/inert materials. This is manifested by the dominance of opaques associated with medium to dark brown palynomorphs. The existence of opaques in Palynofacies 1 is believed not to be attributed to oxidizing depositional conditions, but rather due to “overcooking” of much of the organic matter through the process of thermal overmaturation (TAI 4- to 3+). In such case, the organic matter is thermally exhausted and lost its hydrocarbon generating potential. However, the other remaining mature phytoclasts, AOM, and palynomorphs may still have some potential for dry gas generation. The interval representing Palynofacies 2 within the uppermost part of the Masajid Formation and the lower part of the Kharita Formation is oil prone (assuming the dominant AOM to be marine) and mature (TAI 3, 3- to 2+). Early to peak oil generation would then be suggested for this horizon. The upper part of the Kharita Formation and the Bahariya Formation corresponding to Palynofacies 3 include gas prone materials that are still immature (TAI 2 to 2-) for generation and expulsion.

The studied section in the Ghoroud-IX well, which comprises the Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations, is gas prone/inert and highly mature to overmature (TAI 4- to 3+). Wet and dry gas generations are proposed for this horizon.

**6. Paleoenvironmental interpretation**

The Jurassic–Lower Cretaceous sediments in the northern Western Desert were deposited generally in shallow marine paleoenvironments (Mahmoud et al., 1999). This interpretation is supported by the nature of palynomorphs and the composition of the recovered kerogen content from the Sharib-1X and the Ghoroud-1X wells. Ternary diagrams proposed by Tyson (1993, 1995 fig. 25.4, tab. 25.2) have been used to make paleoenvironmental deductions (Fig. 9).

*6.1. Jurassic (Masajid Formation)*

The lower part of the Masajid Formation (6160–6020 ft; 1878–1835 m, Palynofacies 1) in the Sharib-1X well is characterized by a high percentage of opaque phytoclasts, believed to be derived from the oxidation of translucent woody material during prolonged transport (Tyson, 1993). High values of opaque phytoclasts are often associated with relatively coarse-grained, high energy, organic-poor facies including distributary channel sands, point bars, levees, proximal crevasse splay deposits, shoreface, offshore, and submarine channel sands (Fisher, 1980; Parry et al., 1981; Batten, 1982; Batten and Stead, 2005; Tyson, 1993; Haas et al., 2010).

The AOM–Phytoclast–Palynomorph ternary plot of Palynofacies 1 (Fig. 9A) illustrates that AOM is diluted by high phytoclast input, which are mainly opaques. This suggests a shallow marine, slightly oxic to suboxic environment greatly influenced by run-off from and proximity to the adjacent landmass. Such influence is clearly seen in the lithologic composition of the unit in its lower part, which has a higher clastic to carbonate ratio (Fig. 2). Furthermore, pteridophyte spores dominate the palynomorph assemblage, comprising 55−64% of the total palynomorph, in comparison to pollen (24–36.5%) and microplankton (6–12%) (Fig. 10). The fact that terrestrial microflora account for 88−94% of the palynomorph assemblage reflects proximity to source (e.g., rivers, deltas, etc.). The dominance of pteridophyte spores over pollen grains may also be indicative of riparian, lacustrine and swampy environments on the adjacent landmass (Tyson, 1993; Schrank and Mahmoud, 1998; Mahmoud and Moawad, 2002).

The upper part of the Masajid Formation (6020–5966 ft; 1835–1818 m, Palynofacies 2) is characterized by a marked dilution of the phytoclast content by AOM, which is indicative of a change toward reducing basin conditions. The AOM–Phytoclast–Palynomorph ternary plot of Palynofacies 2 (Fig. 9C) shows that samples are located within palynofacies field VI that Tyson (1993, 1995) interpreted as being indicative of a proximal suboxic–anoxic shelf.

*Classopollis*, a gymnosperm that reflects hot xerophytic conditions, constitutes up to 15% of the total palynomorphs. Its abundance and the presence of such pollen grains *Araucariacites* and *Spheripollenites* suggest a warm dry climate for this interval. The absence of bisaccate gymnosperm pollen, which are usually associated with temperate climates (Sultan,1986) and montane conditions supports this interpretation.

We can conclude from the foregoing discussion that the Masajid Formation was probably deposited in a shallow carbonate platform that experienced periodic encroachment of the shoreline during times of lowered sea level. This would have resulted in the formation of the interspersed clastics (siltstones, shale). Diagenesis affected sedimentation and palynofacies (e.g., dolomitization of the upper portion of the formation), and together with shoreline fluctuation lowered the original percentage of AOM through such processes as syn- and post-depositional oxidation.

*6.2. Cretaceous succession*

*6.2.1. Alam El Bueib, Alamein, and Dahab formations*

Present only in the Ghoroud-IX well, samples of these formations occur mostly in palynofacies field II (Fig. 9B). This suggests that they were likely deposited under dysoxic-anoxic conditions (Tyson, 1993, 1995). Like the Masajid Formation, the samples have high percentages of opaque phytoclasts. Thus, deposition might have occurred close to fluvial sources where phytoclasts were oxidized to opaques during transportation.

Mahmoud and Moawad (1999) studied the palynomorph association of these formations in the Ghoroud-1X well and proposed deposition in a shallow (restricted) marine paleoenvironment based on the nature and composition of the recovered dinoflagellate cysts. Our result confirms their interpretation.

*6.2.2. Kharita Formation*

The palynomorph assemblage of the Kharita Formation in the Sharib-1X well has high pollen percentages (53.5–72.5% of the total palynomorphs) compared to pteridophyte spores (14.5–37.5%) and dinoflagellate cysts (2.5–18%) (Fig. 10). This suggests deposition in a nearshore paleoenvironment. When compared to other sporomorphs, pollen grains are more buoyant, easily transported, and typically increase in numbers offshore (Tyson, 1993, 1995; Traverse, 2007). The extreme abundance of pollen grains together with the fairly high percentages of pteridophyte spores reflect distal deposition within the nearshore zone (probably outer shelf) that was not far from land sources.

The AOM–Phytoclast–Palynomorph ternary plot of Palynofacies 2 in the Sharib-1X well (Fig. 9C) shows a marked dilution of the phytoclast content by AOM in the lower part of the Kharita Formation. This suggests deposition somewhat farther removed from non-marine sources where suboxic–anoxic conditions prevailed (Tyson, 1993, 1995).

The AOM–Phytoclast–Palynomorph ternary plot of Palynofacies 3 for the upper part of the Kharita Formation (Figs. 7, 9D) indicates a sudden change in the kerogen composition; phytoclasts are the dominant kerogen component. Most of the phytoclasts are translucent woody material rather than opaque varieties. This sudden change corresponds to a paleoenvironmental shift toward more proximal depositional conditions close to the source of vegetation (Tyson, 1993).

The sustained high abundance of *Afropollis* (up to 43.5% of the total palynomorphs) co-occurring with diverse *Equisetosporites/Ephedripites* and elaterate pollen is characteristic of the Albian–Cenomanian Elaterates Province of Herngreen et al. (1996). This province had a paleoequatorial distribution corresponding to an arid to semi-arid warm climate (Soliman et al., 1991; El Beialy, 1994b; Aboul Ela et al., 1996; Herngreen et al., 1996; Ibrahim, 2002b; Mahmoud and Moawad, 2002). However, the occurrence of fern spores, mainly produced by hygrophilous plants, suggests the possibility of locally or seasonally humid conditions (Schrank and Mahmoud, 1998).

The AOM–Phytoclast–Palynomorph ternary plot for the Ghoroud-IX well (Fig. 9B) shows high percentages of phytoclasts dominated by opaques for the Kharita Formation. Paleoenvironmental interpretation is the same as that described for the Alam El Bueib, Alamein and Dahab formations (section 6.2.1).

In summary, the Kharita Formation is shallow marine and was deposited under suboxic-anoxic conditions adjacent to a semi-arid to arid hinterland.

*6.2.3. Bahariya Formation*

Figures 7, 8, 9B and 9D show that the Bahariya Formation and underlying Kharita Formation experienced similar depositional conditions in shallow marine environment.

**7. Cretaceous provincialism**

The palynofloral association of the Kharita and Bahariya formations in the Sharib-1X well is comparable to the Albian–Cenomanian Elaterates Province of Herngreen et al. (1996) as follows:

1. Relatively low abundances of fern spores.

2. Absence of bisaccate and trisaccate gymnosperm pollen.

3. Common occurrence of ephedroid gymnosperm pollen such as *Equisetosporites/Ephedripites* and *Gnetaceaepollenites*.

4. Presence of elater-bearing genera such as *Elaterocolpites*, *Elaterosporites*, *Elateroplicites*, *Galeacorna* and *Sofrepites*, which are restricted to this province.

5. High percentage of angiosperm pollen of total sporomorphs (among them, *Afropollis* was extremely abundant).

This assemblage is suggestive of an arid to semi-arid warm climate (Herngreen et al., 1996; Ibrahim et al., 2000), which is equivalent to the African–South American (ASA) Microfloral Province of Herngreen (1974) and Herngreen and Chlonova (1981), the Northern Gondwana Province of Brenner (1976), *Galeacornea* paleophytogeoprovince of Srivastava (1978), the *Elaterosporites* phytogeoprovince of Srivastava (1981), Northern Gondwanan Realm of Batten and Li Wenben (1987) and the mid-Cretaceous elater-bearing phytogeoprovince of Srivastava (1994).

**8. Conclusions**

Palynomorph and palynofacies analyses of 93 subsurface cuttings samples from the Jurassic Masajid Formation and Cretaceous Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations in the Sharib-1X and Ghoroud-1X wells, north Western Desert of Egypt, yielded the following conclusions.

1. A diverse and well preserved record of pteridophyte spores, gymnosperm pollen, angiosperm pollen and dinoflagellate cysts in the Sharib-IX well was used to identify two palynozones:

a. *Systematophora penicillata*–*Escharisphaeridia pocockii* Assemblage Zone (Middle to Late Jurassic).

b.*Cretacaeiporites densimurus*–*Elateroplicites africaensis*–*Reyrea polymorpha* Assemblage Zone (late Albian to early Cenomanian).

These palynozones can be correlated with several previously established zonations in Egypt and other regions of northern Gondwana. The Albian–Cenomanian assemblages of the Kharita and Bahariya formations of the Sharib-1X well belong to the Elaterates Province of Herngreen et al. (1996).

2. Visual assessment of kerogen components was used to evaluate source rock potential, and spore color has formed the basis for determining organic thermal maturation levels as follows:

a. In the Sharib-1X well, highly mature to overmature gas prone/inert source rocks occur within the lower part of the Masajid Formation, whereas mature oil prone source rocks are present in its uppermost part and the lower part of the Kharita Formation. Immature gas prone source rocks exist within the upper part of the Kharita Formation and the Bahariya Formation.

b. Mature to overmature gas prone source rocks in the Cretaceous succession (Alam El Bueib, Alamein, Dahab, Kharita, and Bahariya formations) in the Ghoroud-1X well.

3. Integrating palynofacies analysis and palynomorph distributions, depositional paleoenvironments were inferred:

a. The Masajid Formation was deposited in a shallow marine paleoenvironment under slightly oxic to anoxic conditions. The co-occurrence of abundant thermophilic xerophytic pollen such as *Classopollis*, and hygrophilous fern spores suggest that the adjacent landmass was semi-arid to arid hinterland with local wetland vegetation.

b. The Alam El Bueib, Alamein and Dahab formations were deposited under dysoxic–anoxic conditions in a restricted shallow marine possibly (inner shelf) paleoenvironment adjacent to fluvial sources.

c. The Kharita and Bahariya formations were deposited under suboxic–anoxic conditions in a shallow marine paleoenvironment with fluvial influence. Deposition occurred under an arid to semi arid warm climate with local or seasonal humid conditions.

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## **Figure captions**

Fig. 1. Generalized map of northern Egypt showing the locations of the Sharib-1X and Ghoroud-1X wells (modified from Ibrahim, 2002b).

Fig. 2. Lithology, sample horizons and palynofacies data for the Sharib-1X well (modified from WEPCO, 1971).

Fig. 3. Lithology, sample positions and palynofacies data for the Ghoroud-1X well (modified from WEPCO, 1970; Mahmoud and Moawad, 1999).

Fig. 4. Ranges of some selected palynomorphs in Africa based on the present study and Schrank and Mahmoud (1998), Mahmoud and Moawad (1999, 2002), Palynodata and White (2008) and references therein.

Fig. 5. Correlation of selected late Albian to middle Cenomanian miospore zonations in Egypt and other regions of northern Gondwana.

Fig. 6. Stratigraphic distribution of the recorded palynomorphs in the Sharib-1X well.

Fig. 7. Relative abundances of particulate organic matter (POM) groups within the defined palynofacies of the Sharib-1X well.

Fig. 8. Relative abundances of POM groups within the defined palynofacies of the Ghoroud-1X well.

Fig. 9. Ternary plots of kerogen in the Sharib-1X and Ghoroud-1X wells.

Fig. 10. Relative abundances of palynomorph groups and non-marine/marine indicators in the Sharib-1X well.

**Explanation of plates**

All specimens illustrated are from the Sharib-1X well. The slide number, England Finder reference (when available), and dimensions are given respectively.

**Plate I**

1. *Concavisporites* sp. Slide 5390a; T26/0, lower focus on laesurae, maximum diameter 47 µm.

2. *Deltoidospora mesozoica* (Thiergart) Schuurman 1977*.* Slide 6030a; E46/4, mid-focus, maximum diameter 49 µm.

3, 4. *Deltoidospora minor* (Couper) Pocock 1970*.* Slide 6030a; Q53/0, (3) upper focus, (4) lower focus, maximum diameter 44 µm.

5, 6. *Triplanosporites* sp. Slide 5390a; C19/2, (5) top focus, (6) mid-focus, length 44 µm.

7. *Matonisporites crassiangulatus* (Balme) Dettmann 1963.Slide 5360; maximum diameter 89 µm.

8. *Trilobosporites laevigatus* El Beialy 1994.Slide 5790; maximum diameter 78 µm.

9. *Crybelosporites pannuceus* (Brenner) Srivastava 1977*.* Slide 5390a; G21/1, maximum diameter 64 µm.

10. *Leptolepidites psarosus* Norris 1969.Slide 6030a; V48/4, maximum diameter57 µm.

11, 12. *Elaterosporites klaszii* (Jardiné and Magloire) Jardiné 1967.Slide 5390a; M30/4, (11) top focus, (12) lower focus, maximum width 73 µm.

13. *Elaterocolpites castelainii* Jardiné and Magloire 1965.Slide 6030a; D38/0, mid-focus, maximum dimension 74 µm.

14. *Elateroplicites africaensis* Herngreen 1973.Slide 5490; maximum dimension 69 µm.

15, 16. *Galeacorna causea* Stover, 1963.Slide 6030a; H56/0, (15) mid-focus, (16) lower focus, maximum dimension 54 µm.

17. *Sofrepites legouxae* Jardiné emend. Boltenhagen 1982.Slide 5740; maximum dimension 58 µm.

18. *Callialasporites infirmus* Mahmoud, *in* Mahmoud and Schrank 2003. Slide 5450; maximum diameter 78 µm.

19, 20. *Callialasporites trilobatus* (Balme) Dev 1961.Slide 6030a; H25/0, (19) top focus, (20) mid-focus, maximum dimension 62 µm.

**Plate II**

1. *Araucariacites australis* Cookson ex Couper 1953. Slide 5390a; R53/3, maximum diameter 65 µm.

2. *Equisetosporites concinnus* Singh 1964.Slide 5400; length 97 µm.

3. *Bennettiteaepollenites regaliae* Dino 1994. Slide 5430; length 93 µm.

4. *Spheripollenites psilatus* Couper 1958. Slide 6030a; P52/0, maximum diameter 28 µm.

5, 6. *Classopollis* sp.Slide 6030a; (5) V40/3, maximum diameter 33 µm, (6) W36/4, maximum diameter 36 µm.

7, 8. *Cretacaeiporites densimurus* Schrank and Ibrahim 1995.Slide 6030a; K56/4, (7) top focus, (8) mid-focus, width 52 µm.

9, 10. *Stellatopollis araripensis* (de Lima) Ward 1986.Slide 5390a; V48/0, (9) top focus, (10) lower focus, length (excluding clavae) 60 µm.

11, 12. *Stellatopollis dejaxii* Ibrahim 2002.Slide 5390a; R44/2, (11) top focus, (12) mid-focus, length (excluding clavae) 62 µm.

13, 14. *Retimonocolpites variplicatus* Schrank and Mahmoud 1998. Slide 5390a; K43/2, (13) top focus, (14) lower focus, length 59 µm.

15, 16. *Afropollis kahramanensis* Ibrahim and Schrank 1995.Slide 6030a; O37/4, (15) top focus, (16) mid-focus, length 52 µm.

17, 18. *Afropollis jardinus* (Brenner) Doyle, Jardiné and Doerenkamp 1982.Slide 6030a; G38/3, (17) top focus, (18) mid-focus, maximum diameter 37 µm.

19. *Pennipollis reticulatus* (Brenner) Friis, Raunsgaard Pedersen and Crane 2000.Slide 5390a; N28/0, maximum diameter 24 µm.

20. *Reyrea polymorpha* Herngreen 1973.Slide 5490; length 56 µm.

**Plate III**

1, 2. *Adnatosphaeridium caulleryi* (Deflandre) Williams and Downie 1969.Slide 6030a; K46/0, (1) top focus, (2) mid-focus, central body maximum diameter 62 µm.

3, 4. *Coronifera oceanica* Cookson and Eisenack emend. May 1980.Slide 5650a; C39/4, (3) mid-focus, (4) lower focus, central body width 43 µm.

5, 6. *Xiphophoridium alatum* (Cookson and Eisenack) Sarjeant 1966.Slide 6030a; M29/2, (5) top focus, (6) mid-focus, maximum diameter (including flange, excluding processes) 65 µm.

7, 8. *Sentusidinium rioultii* (Sarjeant) Sarjeant and Stover emend. Courtinat 1989.Slide 6030a; W28/0. (7) top focus, (8) lower focus, maximum diameter 72 µm.

9, 10. *Systematophora penicillata* (Ehrenberg) Sarjeant 1980.Slide 6030a; F28/0, (9) top focus, (10) lower focus, central body maximum diameter, 44 µm.

11. *Florentinia* sp. Slide 5650a; U24/4, central body length 69 µm.

12. *Spiniferites ramosus* (Ehrenberg) Mantell 1854. Slide 5390a; P21/1, length (including processes) 64 µm.

13. *Micrhystridium lymensis* Wall 1965. Slide 6030a; N43/4, central body maximum diameter 26 µm.

14. *Micrhystridium stellatum* Deflandre 1945. Slide 6030a; B49/1, central body maximum diameter (excluding processes) 25 µm.

15-18. Structured phytoclasts. (15, 18) Tracheid tissues, Slides 5470, 5450; (16) Dispersed cuticle, Slide 5450; (17) Spiral vessels (derived from the xylem or from a water conducting tissue), Slide 5450. Images are not to scale.

19, 20. Well preserved (AOM) particles. Slide 5750. Images are not to scale.

21, 22. Biostructured opaque particles. Note the biserial perforation arrangement which indicates that these particles might have been derived from a tracheid tissue (Tyson, 1995). Slide 6110, 5450. Images are not to scale.

23. *Elaterosporites klaszii* (Jardiné and Magloire) Jardiné 1967. (X1850), Scale bar length 20 µm.

24. *Elaterocolpites castelainii* Jardiné and Magloire 1965. (X1400), Scale bar length 20 µm.

25. *Oligosphaeridium complex* (White) Davey and Williams 1966. (X1200), Scale bar length 20 µm.

26. *Florentinia cooksoniae*(Singh) Duxbury 1980. (X1450), Scale bar length 20 µm.