Palaeoenvironmental Reconstruction of the Early to Middle Miocene Sequence in West Central Sinai, Egypt, as Revealed from Fossil Diatoms

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Abstract: A detailed analysis of the diatoms from the sedimentary sequence exposed in Abu Qada basin, west central Sinai, was used to determine the palaeoenvironmental changes during the Lower to Middle Miocene. A total of 85 diatom species and varieties belonging to 37 genera were identified from 154 samples collected throughout the stratigraphic succession. The lithological characteristics of the studied samples varied between sandstone, silty interbeds, sandy shales, shales, and terminated with anhydrite and limestones. These rock units are included in two lithostratigraphic formations (Rudies and Kareem), which are separated by a marked unconformity. The distribution and preservation of fossil diatoms in the sedimentary record are examined with the aim of outlining the temporal and spatial variation in the composition of the diatom assemblages, in order to estimate the changes in depositional environments during the Lower to Middle Miocene. The distributional pattern of the recorded diatom taxa distinguished four diatom eco-zones. The environment of each eco-zone is deduced and a proposed paleobathymetric change and depositional history of the Miocene sediments in the studied area are given.

Key words: palaeoenvironment, Miocene sequence, diatoms, west central Sinai, Egypt

1 Introduction

Diatoms are unicellular algae that are characterized by a siliceous cell wall. These microscopic organisms inhabit virtually every aquatic environment where there is sufficient light for photosynthesis. Their siliceous frustules are well preserved in the fossil record. They are being used increasingly to assess environmental change, because they are very sensitive and respond rapidly to changes in many ecological characteristics (Birks and Koc, 2002). They have narrow optima and tolerances for many environmental variables (e.g., pH of the water, salinity, habitat, nutrient availability, water depth, saprobity, etc.) that make them exceptionally useful in quantifying environmental characteristics within a high degree of certainty (Zalat and Servant-Vildary, 2005, 2007). The close relationship exhibited between contemporary diatom communities and environmental parameters allows numerical estimation of palaeoenvironmental conditions from the sedimentary diatom record by means of transfer functions (Fritz et al., 1991). Therefore, diatoms are considered a powerful tool for environmental monitoring and palaeoenvironmental reconstruction and they are applied widely in palaeoecological studies of different types of environments.

The published diatom research on the Miocene from Egypt and their significance in palaeoenvironmental reconstruction are very limited (Tawfic and Krebs, 1994; Zalat, 1996). Most of the previous studies on the Gulf of Suez and west-central Sinai areas, have focused on stratigraphy, paleontology, sedimentology, geological history and tectonic position. The list of publications is long (including, e.g., National Committee of Geological Science, 1976; El-Heiny and Martini, 1981; Arafa, 1982, 1991; Hosny et al., 1986; Hamza, 1988, 1992; Hermina et al., 1989; Darwish and El-Azabi, 1993; Mahmoud, 1993; Eweda and Zalat, 1996; Wescott et al., 1996; El-Azabi, 1997; Krebs et al., 1997; Marzouk, 1998; Abul-Nasr and Salama, 1999; Soliman, 2000; Sadek, 2001; Barakat et al., 2002; El Beialy and Ali, 2002; El-Deeb et al., 2004; Boukhary et al., 2012 and El-Rayes and Arnous, 2015). These studies have been undertaken, because these Miocene rocks represent the main hydrocarbon-bearing reservoirs in Egypt.

The present study is considered a new detailed contribution on fossil diatoms from the Miocene sediments of Egypt. The main objective is to describe the abundance, preservation, and distribution pattern of
Miocene diatoms in the studied outcrop section in the Abu Qada basin, and to interpret and reconstruct the palaeoenvironments during the early to middle Miocene in the west central Sinai area.

2 Geological Setting and Stratigraphic Framework

2.1 Geological setting

The Miocene sediments of Egypt exhibit rapid lateral and vertical lithological variations, and have a large number of unconformities, reflecting the nature of the tectonically-formed basins in which they were deposited (Said, 1962, 1990; Zalat, 2013). These sediments constitute the most important stratigraphic succession throughout the Gulf of Suez and west-central Sinai area. They attracted the attention of a large number of geologists since the early 20th century, because of their having significantly furnished the source, reservoirs and seals for the oil discovered in the Gulf of Suez area. The Gulf of Suez extends from latitude 27º30’N to 30ºN, and is a large tensional feature caused by the separation of the Nubian and Arabian plates, often referred to as the “Clysmic Rift of Egypt” (Hume, 1921; Said, 1962). This tectonic basin is 60–80 km wide and consists of a 3 to 4 km thick sediment prism that ranges from Miocene to Holocene in age (El-Hedeny, 2005). The dominant features of the Clysmic rift are four tilted blocks, two on the eastern side and two on the western side of the Gulf of Suez. Among them, the Wadi Abu Qada basin is situated close to the eastern part of the Gulf of Suez, in west-central Sinai. Miocene deposits are dominant in this area, and the studied stratigraphic section is delineated by latitude 29º20’ N and longitude 33º02’ E (Fig. 1).

2.2 Stratigraphy

The Miocene deposits in the Gulf of Suez and adjacent areas have been studied and classified by many authors. The first stratigraphic classification was proposed by Moon and Sadek (1923), based on a measured surface exposure at Wadi Gharandal in west-central Sinai. The consultative Stratigraphic Committee of the Egyptian General Petroleum Corporation (EGPC, 1964) has established a lithostratigraphic classification for the Miocene sequence of the Gulf of Suez, wherein the nomenclature for group, formation and member names are derived from their type localities. This classification was slightly modified by the Stratigraphic Sub-Committee of the National Committee of Geological Science (N.C.G.S., 1976), which included the clastic-rich Kareem Formation in the lower Gharandal Group. Later on, Garfunkel and Bartov (1977), Gawad et al. (1986), Hosny et al. (1986), Samuel et al. (1988), Hermina et al. (1989), Krebs et al. (1997) and many others gave some modifications to the Miocene classification of the Gulf of Suez and adjacent areas.

Based on the classification of the National Committee of Geological Science (1976), the Miocene sediments are commonly subdivided into two major rock units. The lower unit is the Gharandal Group of Lower to Middle
Miocene and the upper unit is the Ras Malaab Group of the Middle to Upper Miocene. The lower clastic Gharandal Group is differentiated into three formal units, the Nukhul, Rudies and Kareem Formations, in ascending order; while the upper, mainly evaporitic, Ras Malaab Group includes also three rock units, the Belayim, South Gharib and Zeit Formations, respectively.

The studied stratigraphic section in the Abu Qada area begins in Wadi Abu Qada and continues upward to the north along the western side of Gebel Merrier. The succession is composed of only two lithostratigraphic units belonging to the Gharandal Group (Fig. 2); the lower unit is the Rudies Formation, which is followed unconformably by the Kareem Formation. The detailed lithological description of these units is as follows:

### 2.2.1 Rudies Formation

The Rudies Formation belongs to the Gharandal Group, which was first introduced by Ghorab et al. (1964) to restrict the rock type identified in the type locality at Rudies-2 Well in west central Sinai from depth interval 1840 m to 2620 m. Its thickness and composition were variable, due to the sedimentation processes in a rapidly subsiding fault-controlled basin (Hewaidy et al., 2014). The formation is considered to host the richest oil source rocks in the Gulf of Suez, deposited under the most favorable structural conditions (Schlumberger, 1984; El Ayouty, 1990). In the studied area, this formation represents the Lower to Middle Miocene clastic section. It conformably overlies the Nukhul Formation and unconformably underlies the Kareem Formation and exhibits a highly variable lithology. It is mainly composed of sandstone interbedded with silty shale, marl, argillaceous sandstone, calcareous sandstone and shales, with a thickness of about 328 m. These sediments are characterized by a rich content of diatoms, which denote the Early Miocene (Late Burdigalian) to Middle Miocene (Langhian). Lithologically, the Rudies Formation is subdivided into four formal members, namely, from older to younger, as follows: Mheierrat, Hawara, Asl and Mreir. These rock units are well-developed and exposed at many localities in west-central Sinai, and they are well recognized in the studied Abu Qada depression.

### 2.2.2 Kareem Formation

The Kareem Formation is the youngest rock unit of the Gharandal Group and was first described by the EGPC (1964). It conformably overlies the Rudies Formation and conformably underlies the Belayim Formation. It has a thickness of about 261 m in the Gharib North-2 Well, in the eastern desert, and it ranges from 152 to 250 m in the Gulf of Suez (EGPC, 1964). The Kareem Formation shows excellent sand reservoirs and constitutes one of the main oil source rocks in the Gulf of Suez area (Schlumberger, 1984; Balduzzi et al., 1978). In the study area, the formation attains a thickness of about 77 m. It is composed of white to light grey massive anhydrite in the lower part and followed by grey, highly calcareous shales, grading to marl, with occasional grey argillaceous limestone intercalations in the upper part and white to light grey massive anhydrite interbeds in the lower part. Most of the marine diatom taxa recorded in the Rudies Formation were also found throughout the Kareem Formation and a few of these taxa have a restricted range and form the basis for the biostratigraphy of the Kareem Formation. The formation yielded also a considerable content of calcareous nannoplankton associations, which point to a Middle Miocene (Langhian-Serravallian) age. The Kareem Formation is subdivided into two members, a lower Rahmi Member with a thickness of about 35 m and an upper Shagar Member, which has a thickness of 42 m.

### 3 Materials and Methods

One hundred and forty two samples were collected from the stratigraphic succession located in the Abu Qada basin, at latitude 29°20’ N and longitude 33°02’ E (Fig. 1). The lithological character of the studied samples varies between sandstone, silty interbeds, sandy shales, shales, and is terminated by anhydrite and limestones. Description of the rock units and the locations of the studied samples are shown in a columnar stratigraphic section (Fig. 2).

Diatom taxa were extracted from the sediments using about 5 grams of each sample, which were boiled with about 30–50 ml of hydrogen peroxide solution (25%) for a few minutes, and then 10 ml of hydrochloric acid (20 %) was added in small doses. The sample was rinsed and decanted repeatedly in distilled water to become neutral. The coarse particles were removed by further decantation. The diatom residue was placed in small bottle with distilled water added, to reach a volume of about 20 ml. Smear slides were prepared of each sample by removing 0.1 ml of the suspension from the bottle by pipette and spreading it onto a cover glass (22 mm × 50 mm), dried on a hot plate and mounted in Canada Balsam, with refractive index 1.67.

Microscopic examination was done with phase contrast illumination, normally using a Carl Zeiss photomicroscope with 63´ and 100´ oil immersion objectives. Diatom counts were made on the basis of the first 500 diatom valves per sample at 630´ magnification to record the relative frequency rating of the diatom species for each sample. In the poor samples, a minimum of 250 valves were counted. Intact frustules were counted as two valves.
(Hemphill-Haley, 1993) and fragments consisting of more than one half of a diatom valve were included in the counts (Battarbee et al., 2001). Diatom identification to species level or variety were made based on the works of Hustedt (1930, 1927–1966); Hendey (1964, 1970); Andrews (1976, 1980); Round et al. (1990); Krammer and Lange-Bertalot (1986, 1988, 1991a,b) and Hartley et al. (1996). The recorded diatom taxa, with their relative abundances for each sample, are shown in Figure 3, as follows:

A (abundant) = more than two specimens per field of view
C (common) = one or two specimens per field of view
F (frequent) = one to five specimens per each vertical traverse
R (rare) = one specimen per a few vertical traverses

Preservation of diatoms was determined qualitatively as follows:
G (good) = finely silicified forms present and no alteration of frustules observed;
M (moderate) = finely silicified forms present with alteration;
P (poor) = finely silicified forms rare and fragmented, and robust forms dominant

4 Results

The diatom analysis of the studied Abu Qada succession reveals interesting, diverse and abundant diatom assemblages. A total of 85 diatom species and varieties belonging to 37 genera were recorded from the studied samples. The preservation of the recorded taxa varies from poorly-preserved in some samples to generally moderately and well-preserved in most of the samples. The stratigraphic ranges and the relative abundance of different diatom taxa, including both marine and non-marine forms, are shown in Figure 3. Multivariate statistical analysis, including hierarchical ascending clustering, distinguished four diatom assemblage eco-zones (Fig. 4). Each eco-zone contains distinctive diatom taxa that reflect past environmental conditions. These eco-zones are represented as follows.

(1) Aulacoseira granulata Assemblage eco-zone (DZ. A)

This assemblage is characterized by an abundance of planktonic freshwater diatom species in mudstone samples 76–100 of the Mreir Member. The diversity is low with ten taxa moderately preserved. The freshwater planktonic Aulacoseira taxa (including Aulacoseira granulata, Aulacoseira granulata var. angustissima, Aulacoseira italica, Aulacoseira islandica, Aulacoseira nyassensis and Aulacoseira distans) are the most dominant
species in this zone, and are associated with a low abundance of some tychoplankton taxa such as *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosirella lapponica*. Some sporadically poorly-preserved marine taxa are reported in samples 82–84.

(2) **Aulacoseira granulata - Staurosira construens Assemblage eco-zone (DZ. B)**

This eco-zone is represented by a mixed assemblage of fresh and brackish water diatoms. The freshwater planktonic *Aulacoseira* species are most commonly associated with the frequent occurrence of *Cyclostephanos dubius*. The benthic and epiphytic freshwater forms, such as *Fragilaria ulna*, *Pseudostaurosira brevistriata*, *Opephora* sp., *Encyonema minutum*, *Encyonema silesiacum*, *Gomphonema gracile*, *Amphora libya*, *Placoneis gastrum*, *Surirella ovata*, are distributed in considerable abundance. The brackish water diatom taxa are represented by the common to frequent occurrence of tychoplankton *Staurosira construens*, *Staurosirella lapponica*, *Staurosirella pinnata*, *Fragilaria vaucheriae*, *Tabularia fasciculate*, in combination with benthic and epiphytic

![Fig. 3. Stratigraphic distribution chart of the identified diatom species in the studied section together with diatom ecozones.](image-url)
forms such as Planothidium lanceolatum, Caloneis clevei, Navicula certa, Mastogloia submarginata, Nitzschia palea, Nitzschia communis, Nitzschia fossilis and Surirella fastuosa. This assemblage was represented throughout the samples 101–112, 115 of the Mreir Member of the Rudies Formation.

(3) Actinocyclus ingens Assemblage eco-zone (DZ. C)

This eco-zone is recorded from the middle part of the Rudies Formation with a thickness of about 115 m (Fig. 3). The lower boundary of this zone is defined by the first occurrence of marine diatoms at sample 40 of the Asl Member. The upper boundary is represented by the first appearance of freshwater diatom taxa at sample 76 of the lower part of the Mreir Member. The diatom association is represented by the common to frequent occurrence of such planktonic littoral marine taxa as Triceratium favus, Actinoptychus senarius, Actinoptychus undulatus, Actinocyclus octonarius, Actinocyclus curvatulus, Coscinodiscus radiatus, Coscinodiscus perforatus, Coscinodiscus eccentricus, Paralia sulcata and Anaula mediterraneus var. intermedius, Raphoneis lancettula, Raphoneis amphicoers. The epiphytic and benthic forms are distributed sporadically throughout the interval zone. The common and first appearance of Actinocyclus ingens in this zone points to a late Early Miocene (Late Burdigalian) age (Barron, 1980, 1981, 1985; Harwood and Maruyama, 1992).

(4) Coscinodiscus spp. Assemblage eco-zone (DZ. D)

This assemblage zone is represented by a predominance of planktonic littoral marine diatom species such as Coscinodiscus eccentricus, Coscinodiscus gigas var. diorama, Coscinodiscus noduliferus, Coscinodiscus perforatus, Coscinodiscus radiatus, Craspedodiscus elegans, Craspedodiscus coscinodiscus, Thalassiosira leptopus, Thalassiosira sp.1, Thalassiosira sp. 2, Paralia sulcata, Actinoptychus senarius, Actinoptychus undulatus, Actinocyclus octonarius, Actinocyclus curvatulus, Thalassiothrix longissima, Thalassionema nitzschioides, Epithemia oceanic, Hemiaulus ambiguus, Hemiaulus arcticus, Hemiaulus danicus, Hemidiscus cuneiformis, Licmophora gracilis, Raphoneis parvula and Rhizosolenia bergonii. This assemblage is characteristic of the upper part of the Mreir Member, from samples 116 to 128 and from samples 139 to 148 of the Shagar Member, Kareem Formation. The common occurrence of Coscinodiscus gigas var. diorama in the upper part of the Mreir Member points to a Middle Miocene (Late Langhian) age. However, the occurrence of Craspedodiscus coscinodiscus in the Shagar Member,
Kareem Formation, denotes a Middle Miocene (Serravallian) age (Zalat, 2013).

5 Discussion

Diatoms are very useful for the characterization of depositional environments (Zalat and Servant-Vildary, 2007; Zalat, 2015), because they are highly sensitive and respond rapidly to changes in many ecological parameters. The changes of diatom species dominance and life forms are important tools to reconstruct sea level change, paleosalinity, paleoaltransport, paleohydrodynamics and paleoclimate (Gasse et al., 1987, 1997; Zalat, 2015). Sea level fluctuation causing facies changes is documented in detail by a changing ratio between the three salinity diatom groups (polyhalobous ‘marine’, mesohalobous ‘brackish’ and oligohalobous ‘freshwater’ diatoms).

The depositional history and the paleoenvironments of the studied section in the Wadi Abu Qada basin, west-central Sinai, can be interpreted from the relative abundance and distribution patterns of diatom assemblages, as well as previous knowledge from the literature about the tectonic events and the relative sea level changes during the accumulation of the Miocene sediments in the Gulf of Suez area and west-central Sinai. The results gained from the diatom analysis reflected changes in sea level and water salinity, which, in turn, are related, at least indirectly, to climatic changes and eustatic sea-level fluctuations associated with tectonic movements. The diatom assemblages indicate alteration between fresh, brackish and marine episodes, reflecting the interaction of rainfall and sea level.

At the base of the studied stratigraphic section, the two rock units of the Mheiherrat and Hawara Members of the Rudies Formation were dominated by the argillaceous sandy facies that commonly contained occurrences of calcareous nanoplankton with an absence of diatom taxa. This reflects a warm, shallow to open marine water environment at the beginning of the early Miocene (Early Burdigalian). This also was reflected in the results of Evans (1988), that suggested upper bathyal to upper middle bathyal conditions based on the occurrence of
calcareous nannoplankton and deep water phenotypes of some foraminiferal species belonging to the genera *Uvigerina*, *Bulimina*, *Cassidulina* and *Dentalina*. The sandstones present in the lower part of the Rudies Formation are attributed to submarine fan deposition, derived from the basement cliffs bordering the Gulf rift valley (Balduzzi et al., 1978).

In the subsequent Al ShMember and the lower part of the Mreib Member (samples 40 to 75), the polyhalobous littoral marine diatom taxa of Assemblage Zone C were distributed in significant numbers. The diatom association included planktonic taxa such as *Actinocyclus ingens*, *Actinocyclus octonarius*, *Actinocyclus curvatulus*, *Actinoptychus senarius*, *Actinoptychus undulatus*, *Anaulus mediterraneus* var. *intermedius*, *Coscinodiscus ecentricus*, *Coscinodiscus perforatus*, *Coscinodiscus radiatus*, *Paralia sulcata* and *Triceratium favus*. The epiphytic taxa such as *Rhaphoneis lancettula* and *Rhaphoneis amphiceros* with other benthic diatom species were distributed in low amounts throughout the interval zone. The fossil assemblage reflects a thalassic environment and is indicative of warm, shallow marine water conditions with reduced nutrient redistribution and a rising sea level during a warm arid climate in the Late Burdigalian.

A rapid abundance of diatom taxa comprising different salinity assemblages was observed in the top samples of the Mreib Member of the Rudies Formation. This unit was dominated by shale and mudstone, attaining a thickness of about 200m, deposited during the early middle Miocene (Early Langhian). At the base of this unit (samples 76–79), the well-to-moderately preserved freshwater diatom assemblage of Zone A, consisting mainly of *Aulacoseira* species, were frequently recorded. This was followed by an interval of sediments (samples 80–81) barren of diatoms. Diatom accumulation then increased from samples 82 to 91, which were dominated by eutrophic planktonic freshwater taxa of *Aulacoseira* species. *Aulacoseira granulata* had a maximum abundance with the commonly occurring *Aulacoseira granulata* var. *angustissima*, *Aulacoseira italica*, *Aulacoseira islandica*, *Aulacoseira nyassensis*, and infrequently occurring typhoplankton taxa such as *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosira construens* var. *venter*. The ecological preference of *Aulacoseira granulata* is well described elsewhere (e.g. Hustedt, 1957; Ehrlich, 1973; Kilham et al., 1986, Zalat and Servant-Vildary, 2005, 2007). This species has been specifically recognized as a freshwater planktonic species throughout the world. It is generally considered to be an oligohalobous, alkaliophilous, limnophilous, oligosaprobic, planktonic diatom, common in alkaline freshwater lakes (Hustedt, 1957; Ehrlich, 1973; Foged, 1980; Zalat, 1991, 2000). *Aulacoseira granulata* is also considered a good indicator of eutrophic water and characteristic of a warm humid climate (Zalat, 2015). Therefore, the diatom assemblage is indicative of a freshwater influx into the Abu Qada basin, creating a deeper, eutrophic, slightly alkaline, freshwater environment during a humid warm period at the beginning of the Middle Miocene. The occurrence of some badly-preserved marine diatoms associated with a predominance of freshwater taxa reflects a lowering sea level associated with the invasion of fresh water into the depression.

A mixed assemblage of freshwater and slightly brackish water diatoms (Zone B) was characteristic of the interval from sample 101 to 115. The fresh water association was dominated by a high abundance of oligohalobous, eutrophic planktonic *Aulacoseira* species and commonly of *Cyclostephanos dubius*, which reflects deposition in the deeper parts of an eutrophic, slightly alkaline, fresh to slightly brackish shallow lake. This group was characteristic of Nile Delta and Egyptian Lakes (Zalat, 1995, 2000; Zalat and Servant Vildary, 2005, 2007). The slightly brackish water community was represented by common occurrences of the typhoplankton *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosira construens* var. *venter*, *Staurosirella japonica*, *Staurosirella pinnata*, *Fragilaria vaucheriae*, *Fragilaria ulna*, *Opephora sp.*, *Tabularia fasciculate*, associated with the epiphytic taxa *Planolothidium lanceolatum*, *Encyonema minutum*, *Encyonema silesiacum*, *Gomphonema gracile* and the benthic forms *Amphora libya*, *Caloneis clevei*, *Navicula certa*, *Placoneis gastrum*, *Nitzschia palea*, *Nitzschia communis*, *Nitzschia fossilis*, *Surirella ovata* and *Surirella fastuosa*. The common occurrence of slightly brackish water diatom taxa associated with an abundance of freshwater forms reflects a mesotrophic to eutrophic, fresh to slightly brackish water environment, with a relatively lowered lake level and warm to slightly drier climate at the beginning of the Middle Miocene (Early Langhian age). Furthermore, the occurrence of some mesohalobous taxa such as *Caloneis clevei*, *Mastogloia submarginata*, *Nitzschia communis*, *Nitzschia fossilis*, *Surirella fastuosa* and *Tabularia fasciculate* together with slightly brackish and freshwater forms are indicative of a brackish water environment with increased alkalinity and salinity, which may be due to a lowering lake level with increased evaporation processes in a warm dry climate.

The great abundance of freshwater diatoms in some intervals of the early Middle Miocene (Early Langhian) suggests a lowering of the sea level and intrusion of freshwater into the Abu Qada depression. However, the occurrence of some marine to saline water taxa with a predominance of non-marine diatoms comprising fresh
and brackish water forms indicates deposition in a freshwater to slightly brackish water environment. Moreover, the increase in abundance of eutrophic, oligohalobous Aulacoseira species, in particular Aulacoseira granulata in the samples of the Mreir unit (Zone B and C) reflects deposition in the deeper parts of an eutrophic, alkaline, shallow freshwater lake. In addition, the predominance of the centric planktonic Aulacoseira species indicates a water body of sufficient extent to allow the development of these planktonic floras, and a high concentration of dissolved silica in the surface water (Zalat, 2015).

Correlations with other coeval stratigraphic sections in the Sinai Peninsula and the Gulf of Suez areas indicate that the fresh and brackish water environment was localized in the Wadi Abu Qada area, in particular during the deposition of the Mreir Member at the beginning of the Middle Miocene. This is explained by uplift and tilting of the bounding faults separating the Wadi Abu Qada - Gebel Gushia block from adjacent rift blocks, where normal marine conditions prevailed (Scott and Govean, 1986).

On the other hand, there are prominent dissolution intervals of diatoms that occur in the Asl and Mreir Members of the Rudies Formation. These intervals of poor diatom preservation with scarce occurrence to an absence of taxa fairly correspond to the periods from samples 46–50 (Event A), 55–58 (Event B), of the Asl Member (Late Burdigalian); 80–81 (Event C), 85 (Event D), 92–95 (Event E), 98–100 (Event F), and 113–114 (Event G) of the Mreir Member (Early Langhian). Because the preservation and abundance of diatoms in sediments is directly related to their abundance in the overlying surface waters, therefore, the absence of diatoms or rare occurrence of poorly preserved forms could result due to reduction in the upwelling or reduced levels of primary productivity, where the surface water was poor in nutrients. Furthermore, the diatom-devoid intervals in the clay-rich Mreir unit may also be due to increased terrigenous components, or result from ecological exclusion or chemical decomposition from the relatively warm fresh waters during the early Middle Miocene. These poor or barren diatom episodes may coincide with the start of a global fall in sea level in the period of major cooling at the start of the Middle Miocene. The rapid progress of cooling and successive warming with dry episodes may cause a decline in diatom abundance in the surface waters and result in poor diatom preservation.

The freshwater environment is shifted into marine conditions in the upper part of the Mreir Member of the Rudies Formation and the Shagar Member of the Kareem Formation during the Late Langhian- Serravallian. The diatom assemblage (Zone D) was dominated by temperate to subtropical littoral marine indicators such as Actinoptychus senarius, Actinoptychus undulatus, Actinocyclus oceanicus, Actinocyclus ehrenbergii, Actinocyclus curvatulus, Annellas californicus, Coscinodiscus asterompholus, Coscinodiscus biangulatus, Coscinodiscus decrescens, Coscinodiscus eccentricus, Coscinodiscus gigas var. dionara, Coscinodiscus lewsianus, Coscinodiscus marginatus, Coscinodiscus nitidus, Coscinodiscus oculus-iridis, Coscinodiscus radiatus, Coscinodiscus perforatus, Coscinodiscus eccentricus, Craspedodiscus elegans, Craspedodiscus coscinodiscus, Thalassiothrix longissima and Thalassionema nitzschioides. The diatom association also contained a limited amount of warm fresh to slightly brackish water taxa in the upper part of the Mreir mudstone Member. The common occurrence of large, robust, centric diatoms Coscinodiscus spp. with long needle-like diatoms such as Thalassionema spp. with Thalassiothrix longissima and Thalassionema nitzschioides are indicative of strong coastal upwelling and high productivity during the Middle Miocene (Late Langhian –Serravallian). Coscinodiscus marginatus is apparently adapted to a high nutrient supply and a quite large range of optimal temperature (5°C–13°C) for high flux. It is considered to be an indicator of autumn/winter conditions as well as a probable cool-transitional form (Takahashi 1986). The continuous occurrences of Coscinodiscus marginatus in combination with other Coscinodiscus spp. in the samples from the upper part of the Mreir unit and the Shagar Member might show marked evidence of coastal upwelling in the warmer transition zone. The highest abundance of littoral marine planktonic taxa during Late Langhian to Serravallian age probably corresponds to winter deposition or heavy winter rains with coastal upwelling of nutrient-rich waters.

The diatom assemblage (Zone D) also contained consistent representatives of warm-water taxa such as Hemidiscus cuneiformis, Thalassiosira convexa, and Coscinodiscus nodulifera. This assemblage is also indicative of the relatively warm-temperate surface waters that extend during the deposition of the upper part of the Mreir Member and the Shagar Member of the Kareem Formation throughout the Middle Miocene. Furthermore, the occurrence of these taxa in samples of the Shagar Member and the presence of an algal limestone bed at the uppermost part of the section reveals that the depositional environment was shallow to slightly open marine, during a warm, tropical to subtropical humid climate. This can also be confirmed by the occurrence of some calcareous nanoplanckton in the sediments.

In the Rahmi Member of the Kareem Formation, diatoms quickly disappear and highly evaporative
processes increase to form the evaporitic deposits at the beginning of the late Middle Miocene in the studied area. This may be due to subsequent faulting along the Gulf of Suez during this time, which caused a relative lowering of the sea level in an episode of a regressive nature. The restricted conditions combined with an arid climate led to deposition of the Rahmi evaporites, which overly the Langhian shales of the Mreir Member.

6 Conclusions

The paleoenvironmental history of the Early to Middle Miocene was estimated from diatom analysis of the Abu Qada stratigraphic section in west-central Sinai. The results reflected changes in water salinity and sea level change, which in turn are related to climatic changes and eustatic sea-level fluctuations associated with tectonic movements. During the Early Miocene (early Burdigalian age), the lower part of the Rudies Formation was deposited in a warm, shallow to open marine water environment. The frequent occurrence of littoral marine planktonic diatom species (Zone C) in the middle part of the Rudies Formation (Asl and the lower part of the Mreir shale Members) point to continuous deposition in warm, shallow marine conditions with reduced nutrient redistribution during the early Miocene (Late Burdigalian). This is followed abruptly by the first occurrence of freshwater diatoms (Zone A), combined with some slightly brackish forms in the middle part of the Mreir Member, which indicate that an eutrophic, warm, slightly alkaline freshwater environment prevailed at the beginning of the Middle Miocene (Early Langhian age). These non-marine intervals may coincide with sea level lowering events during this time.

The increased freshwater influence was the result of a rising water table during a period of rising sea level. As transgression continued, the barrier that separated the Wadi Abu Qada depression from marine waters was eventually breached. Fresh water then filled the depression to form a large freshwater lake at the beginning of the Middle Miocene (Early Langhian), which is converted to a brackish water lake during the late Early Langhian. This reflects that the local occurrence of fresh to brackish water depositional environments was controlled by structural reorganization of fault blocks in the Suez Rift in response to the ‘mid-clysmic’ tectonic event.

Transgression of the sea occurred again and the marine water invaded the brackish water lake and deposited littoral planktonic marine diatoms (Coscinodiscus Zone D) with some brackish water forms in the upper part of the Rudies Formation during the Late Langhian. This marine interval reflects a time of extensive marine transgression with relatively warm-temperate high coastal upwelling of nutrient-rich water conditions, following a major drop of the sea level at the Burdigalian/Langhian transition (Hardenbol et al. 1998).

Eventually a hypersaline lagoon formed in what previously had been a brackish water lake at the beginning of the late Langhian - Serravallian and depositing the Rahmi evaporites of the Kareem Formation. This rock unit was completely devoid of any fossils and denotes the abrupt facies change and basin restriction during early Kareem Formation time (Early Serravallian age). It is followed by the Shagar Member, which includes an upper 42 m thick sequence of calcareous mudstone, sandy marl and ending with algal limestone. This sequence was characterized by common to frequently occurring littoral marine planktonic diatom taxa of Coscinodiscus Zone D. The diatom assemblage reflects marine transgression with relatively warm high coastal upwelling of nutrient-rich water conditions during the Serravallian age.

In general, the diatom occurrence is discontinuous throughout the studied Miocene succession, with intervals of rich diatom assemblages separated by non-productive intervals of devoid or reworked, fragmented diatoms. Dissolution of diatom assemblages is represented typically in the studied Miocene section indicating a marked decline in the production of diatoms in surface waters with high terrigenous input which led to dilution of diatom frustules during the time of diatom deposition. Common-to-abundant distribution of such dissolution-resistant marine taxa such as Coscinodiscus spp. and Triceratium spp. in the upper part of the Mreir and Shagar members is due to rising sea level and coastal upwelling of nutrient-rich waters.

The Early/Middle Miocene boundary is placed in the middle part of the Mreir Member. This boundary reflects a rapid change in the environment of deposition from shallow marine to lacustrine, which is related to sea-level fall that outpaced subsidence at the beginning of the Middle Miocene.

Acknowledgements

The author is grateful to the Editor-in-Chief and the anonymous reviewers for their insightful and helpful comments that greatly improved the manuscript.

Manuscript received Jan. 1, 2017 accepted Aug. 27, 2017
edited by Jeff Liston and Fei Hongcai

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**Appendix**

Taxonomic List of diatom taxa considered in this paper in alphabetical order of generic epithets.

*Actinocyclus ingens* Rattray 1890

*Actinocyclus curvatus* Janisch 1878

*Actinocyclus octonarius* Ehrenberg 1838

*Actinocyclus octonarius var. tenellus* (Brébisson) Hendey 1964

*Actinocyclus splendens* (Shadboldt) Ralfs in Pritchard 1861

*Actinocyclus vulgaris* Schum 1867

*Amphora libya* Ehrenberg 1840

*Anaulus mediterraneus* var. *intermedius* Grunow 1882

*Aulacoseira distans* (Ehrenberg) Simonsen 1979

*Aulacoseira granulata* (Ehrenberg) Simonsen 1979

*Aulacoseira granulata var. angustissima* (O. Müller) Simonsen 1979

*Aulacoseira italic* (Ehrenberg) Simonsen 1979

*Aulacoseira nyassensis* (O. Müller) Simonsen 1979

*Aulacoseira varians* (Agardh) Simonsen 1979

*Aulacosira islandica* (O. Müller) Simonsen 1979

*Biddulphia aurita* (Lyngbye) de Brébisson 1838

*Biddulphia regia* (Schultze) Ostenfeld 1908

*Caloneis clevei* (Lagerstedt) Cleve 1894

*Coscinodiscus asterompholus* Ehrenberg 1840

*Coscinodiscus biangulatus* Schmidt 1878

*Coscinodiscus decrescens* Grunow 1878

*Coscinodiscus eccentricus* Ehrenberg 1840 = *Thalassiosira eccentrica* (Ehrenberg) Cleve emend Fryxell & Hasle 1977

*Coscinodiscus gigas* var. *diorama* (Schmidt) Grunow 1884

*Coscinodiscus marginatus* Ehrenberg 1843

*Coscinodiscus nitidus* Gregory, 1857

*Coscinodiscus nodulifer* Schmidt 1874 = *Azpeitia nodulifera* (Schmidt) Fryxell & Sims in Fryxell, Sims & Watkins 1986

*Coscinodiscus oculus-iridis* Ehrenberg 1840

*Coscinodiscus perforatus* Ehrenberg 1844

*Coscinodiscus perforatus var. cellulosus* Grunow 1884

*Coscinodiscus radiatus* Ehrenberg 1840

*Craspedodiscus coscinodiscoides* Ehrenberg 1844

*Craspedodiscus elegans* Ehrenberg 1844

*Cyclodiscus dubius* (Fricke) Round 1982

*Depthineis biseriata* (Grunow) Andrews 1979

*Depthineis surirella* (Ehrenberg) Andrews 1979

*Diploneis bombus* Ehrenberg 1844

*Encyonema minutum* (Hilse ex Rabenhorst) Mann in Round et al. 1990

*Encyonema silesiacum* (Bleisch ex Rabenhorst) Mann in Round et al. 1990

*Encyonema minutum* (Hilse ex Rabenhorst) Mann in Round et al. 1990

*Encyonema silesiacum* (Bleisch ex Rabenhorst) Mann in Round et al. 1990

*Encyonema minutum* (Hilse ex Rabenhorst) Mann in Round et al. 1990