Palaeoclimatic conditions leading to development of sapropelic layers in upper Lower Miocene rocks around Siwa Oasis, Western Desert, Egypt

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Abstract. Sapropelic layers were identified in the two informal units (unit I, II) of the Moghra Formation (Aquitanian-Burdigalian), where three stratigraphic sections were studied and sampled from west El Qara, Siwa, and El Arag oases**,** northern Western Desert of Egypt. Samples from the two informal units of the Moghra Formation generally contain 0.6-1.8% total organic carbon and demonstrate that the upper Lower Miocene deposits of the eastern Mediterranean Sea at the area around Siwa Oasis contain more than eight sapropelic layers. In the west El Qara and Al Arag sections, the middle unit of the Moghra Formation (unit II) shows an increase in miliolid foraminifera, accompanied by an increase in Rotaliidae (mainly *Ammonia beccarii*) which indicates fluctuations in salinity towards brackish conditions. Moreover, the benthic foraminiferal fauna in sapropelic layers of unit I of the Moghra Formation is characterized by low species diversity typical of high nutrient and low oxygen conditions. The presence of benthic foraminifera in the sapropelic layers suggests that the surface sediment was oxic.

▪ ***Keywords:*** *Egypt, Western Desert, Lower Miocene, Palaeoclimatology, Palaeoecology.*

Introduction

A sapropel is defined as a discrete bed more than 1 cm-thick, containing more than 2.0% organic carbon by weight, whereas a sapropelic layer contains 0.5-2.0% organic carbon by weight (Kidd et al. 1978). Vergnaud-Grazzini et al. (1977), Kidd et al. (1978), Rohling (1994), Cramp & O'Sullivan (1999), Meyers (2006) and Kuhnt et al. (2007) demonstrated the deposition of sapropels and sapropelic layers in the eastern Mediterranean since about the middle Miocene.

There are two explanations for the existence of Mediterranean sapropels and sapropelic layers: (1) anoxia; sapropelic layers were deposited as the result of basin-wide stagnation and anoxia (Olausson 1961; Van Straaten 1972; Sigl & Müller 1975; Vergnaud-Grazzini et al. 1977; Kidd et al. 1978); and (2) productivity; increased plankton productivity resulted in a high organic carbon content of sapropelic deposits in well oxygenated bottom waters (Calvert 1983, 1990; Calvert & Pedersen 1992, 1993).

The Miocene deposits in the northern Western Desert are represented by deltaic sediments of the Moghra Formation (Aquitanian-Burdigalian). Its fluvial sands were deposited by a northerly flowing river system that drained the area south of the present Qattara Depression. The Oligocene rivers flowing to Fayium were shifted northwestward building the Lower Miocene delta at the southern part of the present Qattara Depression (Issawi et al. 1999). There the Oligocene – Miocene boundary is marked by an unconformity surface, which is represented by thick glauconitic clay gravels followed upwards by a thick package of fragments and harder limestone gravels embedded in a carbonate matrix.

Sapropelic layers were identified in the two informal units of the Moghra Formation (Aquitanian-Burdigalian). Three stratigraphic sections were sampled and studied from west El Qara, Siwa, and El Arag oases (Text-fig. 1). The results of these investigations provide a good base for any further geological investigations, especially concerning petroleum research.

The analysed interval corresponds to a time of so-called mid-Miocene warmth, which spans the late Early and early Middle Miocene. During a climax within this period at V16 Ma, sea-surface temperatures as well as deep waters at high latitudes were warmer than today (Shackleton & Kennett 1975), marking the warmest episode during the entire Neogene (Savin 1977; Flower & Kennett 1994).

According to Abreu et al. (2000), the mid-Miocene warmth coincided with a peak in sea level of 10 Myr in duration. Various independent data confirm the world-

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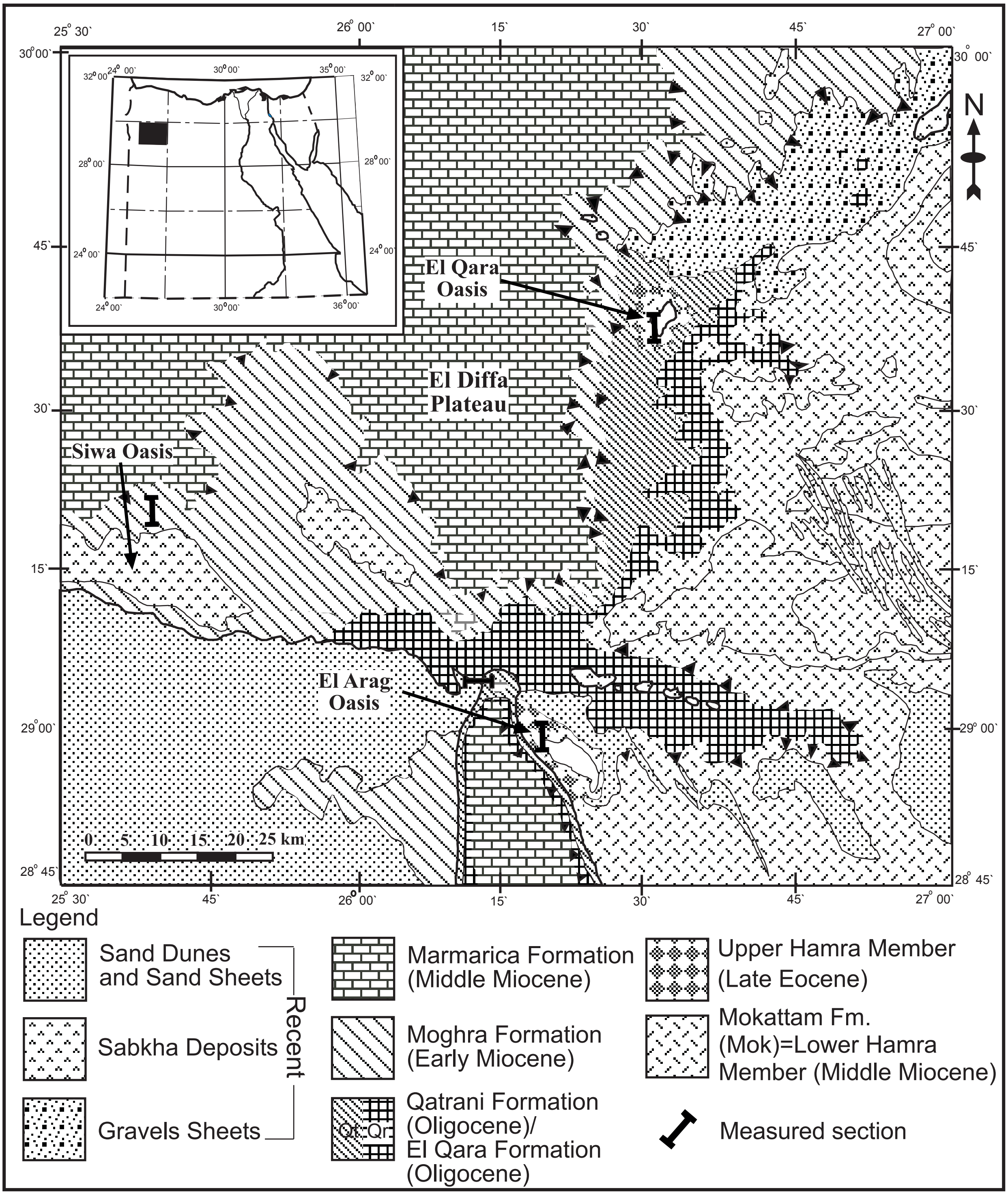
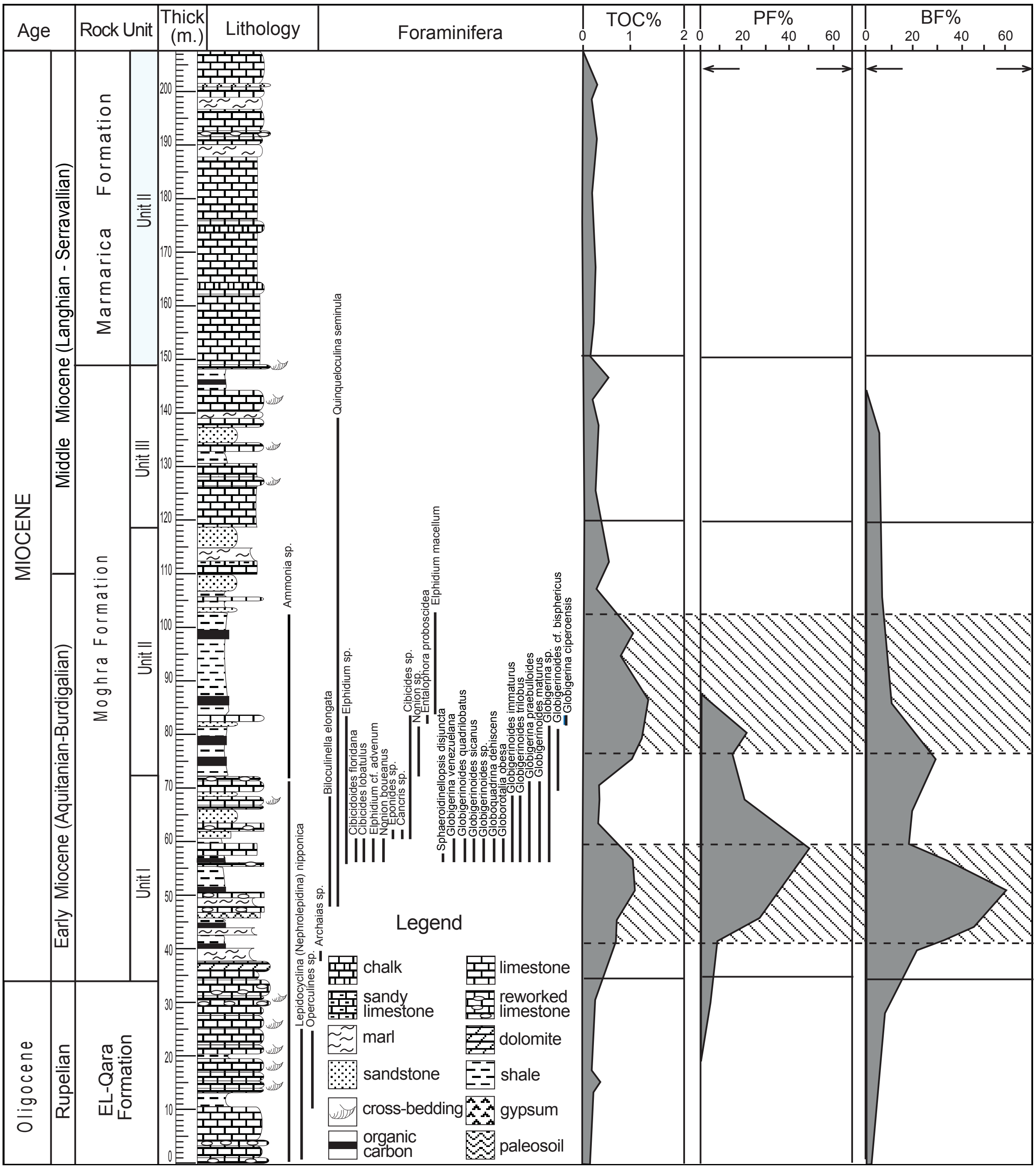


Text-fig. 1. Geological map of Siwa-El Qara area, northern Western Desert, Egypt.

wide character of this mid-Miocene warming. Warming climate indicators include stable isotope ratios of the foraminiferal record (Shackleton & Kennett 1975; Wright et al. 1992; Flower & Kennett 1994), benthic and planktonic foraminiferal migration patterns (Hornibrook 1992) and diversities (Jenkins 1973), presence of extratropical carbonates in southern Australia (McGowran & Clarke 1997) and the distribution of tropical mollusks and mangrove swamps in Japan (Ogasawara 1994) and South America (Tsuchi 1992).

The primary objectives of this paper are to evaluate evidence for or against two rival hypotheses for the development of sapropelic layers at Siwa Oasis in the eastern Mediterranean Sea by (1) documenting the productivity models associated with the transition from the last Oligocene volcanic to the Miocene epoch and by (2) delineating the precise chronology of the palaeo-oceanographic events.



Text-fig. 2. Distribution chart of foraminifera, plots of total organic carbon (TOC), planktonic foraminifera (PF), and benthic foraminifera (BF), El Qara section.

Geological setting

In the northern part of the Western Desert, between the Ras Qattara Ridge and the Mediterranean Sea, the prospective northern basins contain up to 6000 m of sediments (WEC 1995). The Siwa Basin is a north-south oriented Palaeozoic basin that covers wide stretches in the north-western reaches of the Western Desert and can be considered as a northern extension of Libya's Kufra Palaeozoic Basin. It contains thick Palaeozoic sedimentary successions ranging from the Cambrian to the Carboniferous. Jurassic or Lower Cretaceous sediments are lacking but a thick Eocene fill is present.

In the northeastern parts of the Western Desert, many local folds and flexures were developed in a general NE-SW orientation. This trend of structures is known as the "Syrian Arc System" (Krenkel 1924). The resulting uplift structures acted as islands in the Paleocene depositional basin. The Paleocene basin did not include the Western Desert as the Cretaceous or the subsequent Eocene basin did.

Later on, the Eocene marine transgression covered most of the northern Western Desert. This resulted in the deposition of carbonates and shales of typical deep marine facies in most of the Western Desert, at least until the Middle Eocene.

By the close of the Middle Eocene, uplift of the land started, regression of the sea commenced, and Upper Eocene deposits within the Western Desert were mainly restricted to its northern part. South of latitude 29° 30' N, no Upper Eocene deposits were recorded.

During Oligocene times, the sea regressed further. The land area was subjected to denudation. Subsidence along the northern shores of Africa and consequently the northern Western Desert led to the formation of structurally controlled basins in which marine Oligocene sediments were deposited. The Oligocene sediments are associated with volcanic eruptions, most abundant in the Fayium area and Bahariya Oasis (Western Desert), where thick basalt sheets and dolerite hills have been recorded.

In the early part of the Miocene, there occurred a general subsidence of the

A

B

C

Text-fig. 3. A. Large-scale tabular cross-bedded limestone of the Moghra Formation (unit I), Siwa section. B. Sapropelic layer, Siwa Oasis (Moghra Formation, unit I). C. Small-scale tabular cross-bedded limestone of the upper unit of the Moghra Formation (unit III), west El Qara section. A-C: Hammer for scale.

land areas causing the sea to advance southwards across the northern part of the country to beyond Siwa Oasis. Along the Mediterranean coast, the transgression rapidly covered the northern Western Desert, the present Nile Delta, and the coastal area of Sinai. Rifts parallel to the coast created local basins, which received more sediments than the peripheral areas. The Oligocene rivers moved northward and an Early Miocene delta was developed at the Moghra Oasis (Issawi et al. 1999).

Material and methods

For the present study, 100 rock samples were collected from west El Qara, El Arag, and Siwa oases. For microfossil investigation 70 soft-rock samples have been prepared, following standard micropalaeontological methods. The first 100 grams from each sample were dried in an oven at 80-100 C° for about 12 hours then soaked for about 24 hours in 10-15% hydrogen peroxide solution. When the chemical reaction was completed, the treated samples were sieved through a 63 mm and 125 mm screen and then dried. Each dried residue was passed through a microsplitter until about 500 planktonic and benthic foraminifera were left in the last split. The foraminiferal species were identified (Plate 1) and counted for the 70 soft-rock samples; abundance of species was calculated on the basis of occurrence in the 125 mm size fraction.

Sapropelic layers were identified in each of the sections sampled in detail, and total organic carbon (TOC) was determined for each sample as percent of sample lost during acid digestion.

Clay-sized mineralogy was studied by semi-quantitative estimates of relative abundance of smectite, illite, chlorite and kaolinite using weighted peak areas and appropriate intensity factors (Carroll 1970).

Stratigraphy

Miocene rocks occupy about one-eighth of the total surface of Egypt (Ball 1952). Miocene sediments can be classified into two facies; namely the Red Sea Facies and the Mediterranean Facies. The study area includes many depressions (El Arag, Siwa) and the extreme western part of the Qattara Depression (Mediterranean Facies). The top surface overlooking these depressions is known as El Diffa Plateau.

Said (1962) described the outcropping Miocene sediments under two formation names; Moghra at the base and Marmarica at the top, whereby the Moghra Formation rests on basalt flows or continental Oligocene sediments. Issawi et al. (1999) classified the Mediterranean Facies into three subfacies; North Western Desert, Delta; and Northern Sinai. The present study deals with the North Western Desert subfacies. In the following, the sections measured by the authors are briefly described.

Moghra Formation (Aquitanian-Burdigalian)

Lower unit (Unit I)

West El Qara section (Text-fig. 2).- The lower unit of the Moghra Formation (unit I) rests on Oligocene sediments (Rupelian). The base of the about 40 m composite section is represented by a black manganese oxide band, 50 cm in thickness, where the upper part is more calcareous and composed of large-scale tabular cross-bedded limestone (Text-fig. 5) and massive coquina limestone with minor sandstone intercalations.

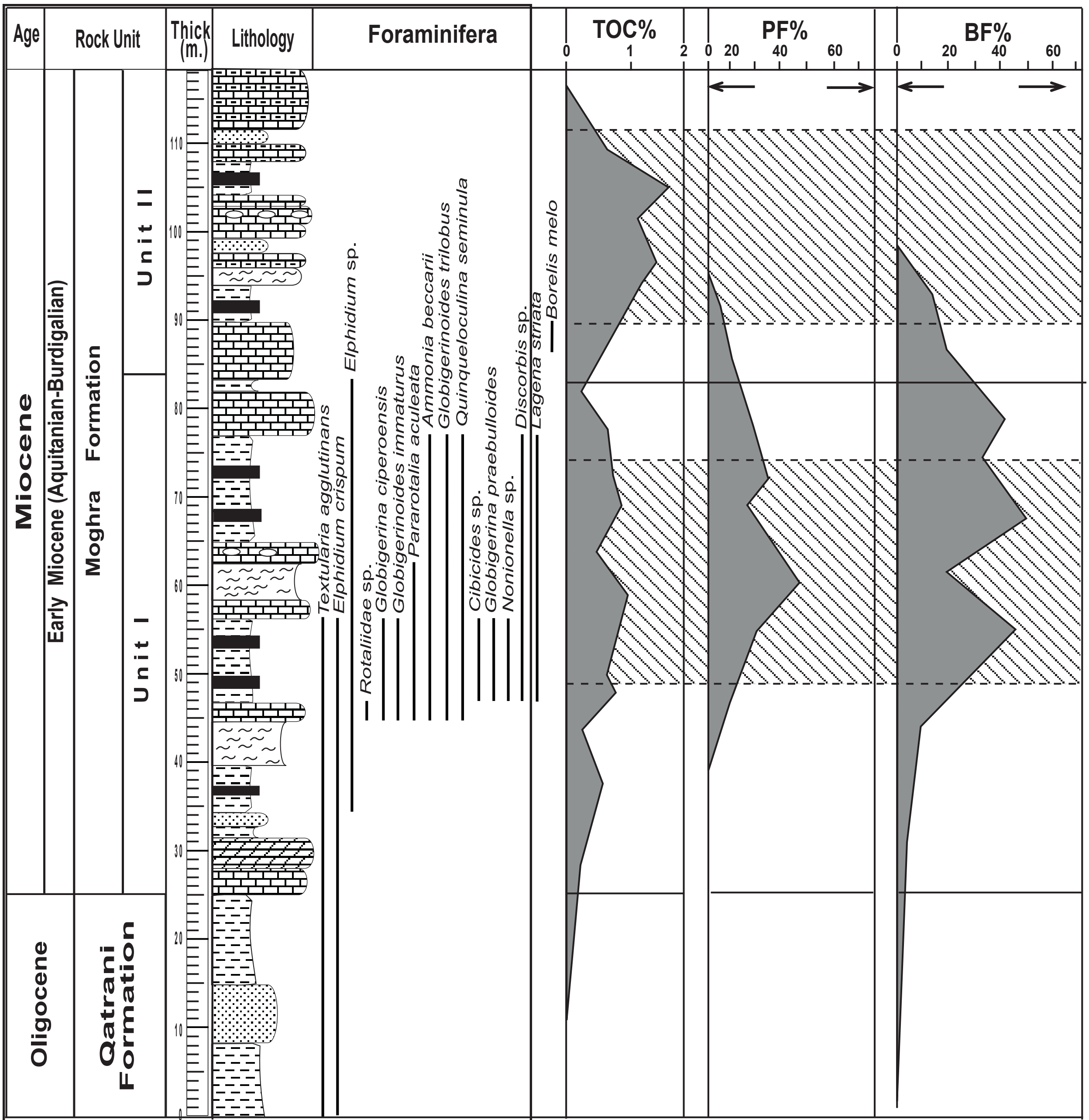
The benthic foraminiferal assemblage consists of *Ammonia* sp., *Cancris* sp., *Cibicidoides floridana, Cibicides lobatulus, Elphidium* cf. *advenum*, *Eponides* sp., *Nonion* sp., *N. boueanus, Archaias* sp., *Biloculinella elongata*, and *Quinqueloculina seminula.* The planktonic assemblage is represented by *Globigerina ciperoensis*, *Gg. praebulloides, Gg. angustiumbilicata, Gg. venezuelana, Globigerinoides* cf. *bisphericus, Gs. immaturus, Gs. quadrilobatus, Gs. sicanus, Gs. trilobus, Globoquadrina dehiscens*, and *Globorotalia obesa* (Pl.1).

El Arag section (Text-fig. 4).- At this locality, the lower unit rests on the Oligocene Qatrani Formation with a pronounced unconformity. About 55 m of the lower unit were measured. They are composed mainly of siliciclastic sediments interbedded with limestone, dolostone, marl, and olive shale. The sediments of this formation are moderately rich in macrofossils. The benthic foraminifera are represented by *Textularia agglutinans*, *Nonionella* sp., *Lagena striata, Quinqueloculina seminiula, Ammonia beccarii, Elphidium crispum, E. advenum, Discorbis* sp., and *Cibicides* sp. The planktonic foraminifera are represented by *Globigerina praebulloides, Gg. ciperoensis, Globigerinoides trilobus* and *Gs. immaturus* (Pl. 1).

Siwa Oasis section (Text-fig. 5).- From a lithological point of view the authors cannot correlate this section with the west El Qara and El Arag sections. The Moghra Formation attains a thickness of 44 m. The base of the section is not exposed, while the top is covered by the Marmarica Formation. The Moghra Formation is characterized by the following benthic foraminifera; *Ammonia beccarii, Elphidium crispum*, *Cibicides* sp., *Lenticulina* sp., *Biloculinella elongate*, and *Quinqueloculina seminula* (Pl. 1).

Middle unit (Unit II)

West El Qara section (Text-fig. 2).- The middle unit of Moghra Formation (unit II) is composed of 46 m of olive shale with gypsum streaks including hard sandstone and thin bands of coquina limestone at the base and near the top. It is characterized by the following benthic and planktonic foraminiferal assemblage; *Nonion* sp., *Elphidium* sp., *E. macellum, Ammonia beccarii, Cibicides* sp., *Quinqueloculina seminula*, *Biloculinella elongata*, *Globigerina* sp., *Gg. ciperoensis* and *Globigerinoides* cf. *bisphericus* (Pl. 1).



Text-fig. 4. Distribution chart of foraminifera, plots of total organic carbon (TOC), planktonic foraminifera, and benthic foraminifera, El Arag section.

El Arag section (Text-fig. 4).- The middle unit is composed of 37 m of sandy limestone, marl, greyish white mudstone, a thin bed of conglomerate, and olive shale. The sediments of this unit are more calcareous and unfossiliferous, except for some bryozoans at the base.

The upper unit (Unit III)

The upper unit of the Moghra Formation (unit III) is represented only at the west El Qara section (Text-fig. 2) and composed of 30 m of yellow to brown sandy coquina limestone with some intercalations of greenish-yellow marl, calcareous sandstone, and olive shale at the base, followed upwards by small-scale tabular cross-bedded limestone, faintly yellow coquina limestone, and red cross-bedded sandstone. Generally, benthic foraminiferal assemblages are represented only by *Quinqueloculina seminula.*

Marmarica Formation (Langhian-Serravallian)

In the study area, the formation varies in thickness from 74.3 m at West El Qara to 114.4 m at Siwa (Text figs. 2, 5), and has not been recorded at El Arag. The Marmarica Formation is composed mainly of limestone, dolostone, and marl.

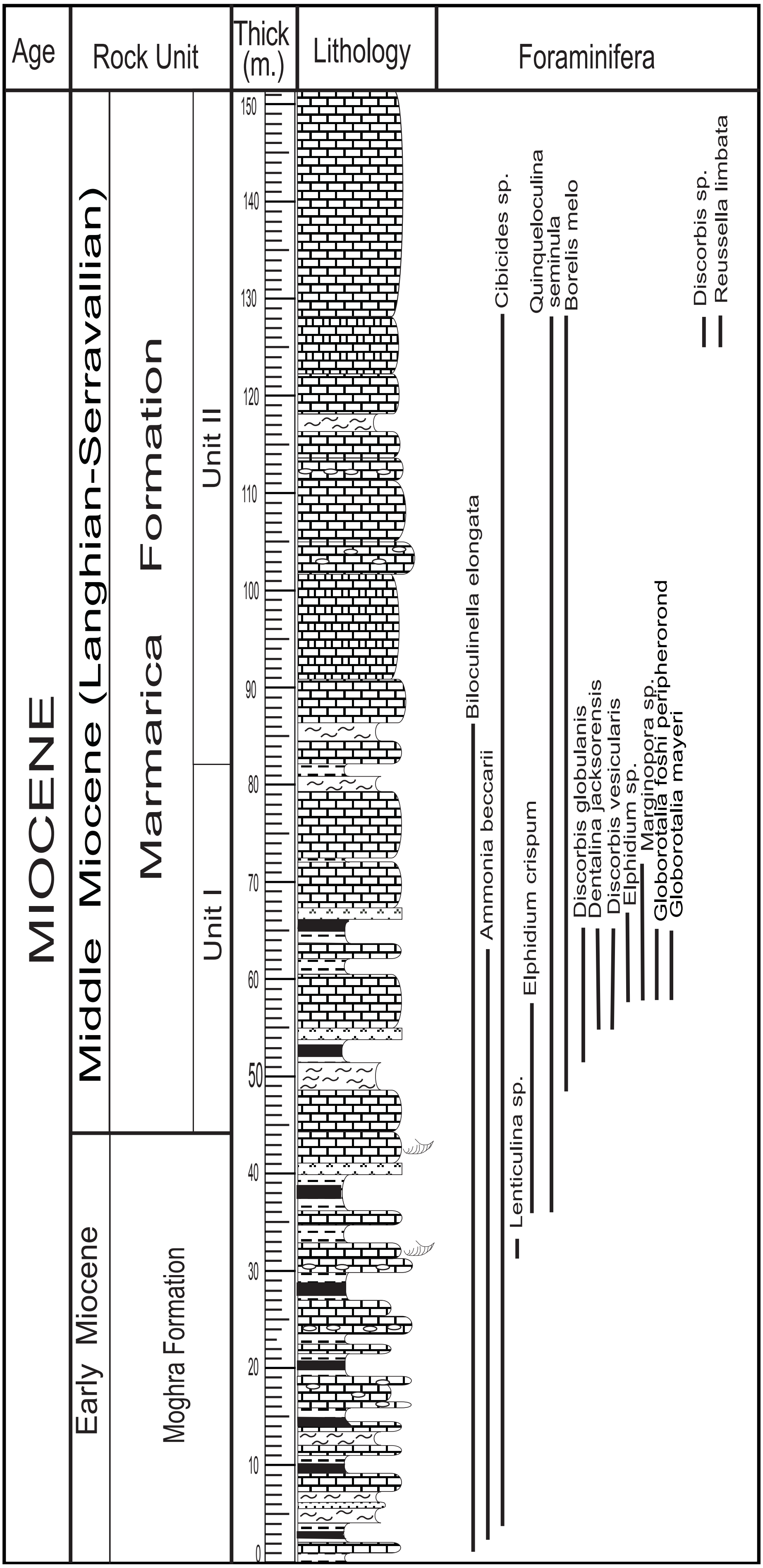
Data

Sediments

All sediments of the Moghra Formation (Aquitanian-Burdigalian) of the three sections were deposited through hemipelagic rain as indicated by the abundance of clay-sized particles, paucity of terrigenous sand-sized particles, and lack of resedimented beds. Nevertheless, fluviomarine conditions are recognized in the upper unit of the Moghra Formation and the upper unit of the Marmarica Formation, where remarkable cross-bedding is noticed at Siwa and west El Qara sections. The El Arag section is devoid of cross-bedded limestone.

The middle unit (unit II) of the Moghra Formation is composed of olive shale, similar to the lower and upper units of the same formation but with high contents of organic carbon. Sediments display distinctive parallel lamination, which is associated with colour banding. The clay fraction of the sapropelic layers of unit I and unit II of the Moghra Formation is characterized by a noticeable decrease in smectite and kaolinite and an increase in illite and chlorite.

The lower unit of the Marmarica Formation (Langhian-Serravallian) consists of greenish-grey to green shale, soft, laminated, calcareous, with vertical cracks filled with gypsum, and highly fossiliferous. The upper unit



Text-fig. 5. Distribution chart of foraminifera, Siwa section.

is recorded at Siwa and El Qara sections, and consists of white limestone with few marl interbeds. Limestones represent about 94% of the total thickness of this unit.

Total organic carbon (TOC)

West El Qara section.- Samples from the lower and upper unit of the Moghra Formation generally contain total organic carbon ranging between 0.6-1.0% by weight, but in samples from the middle unit of the Moghra Formation TOC ranges between 1.1-1.4% by weight.

Siwa Oasis section.- Samples from grey clay and olive shale of the Moghra Formation at the Siwa section generally contain 1.6-1.2% TOC by weight.

El Arag section.- Samples from the lower unit of the Moghra Formation generally contain 0.8-1.2% TOC by weight, whereas samples from the middle unit contain 1.3-1.8% TOC. Samples from the three informal units of the Moghra Formation generally contain 0.6-1.8% TOC, and demonstrate the presence of more than eight sapropelic layers in the eastern Mediterranean Sea around Siwa Oasis in the upper Lower Miocene deposits.

Generally speaking, in samples from the southern part of the study area (El Arag section), TOC increases to 1.8% in the Moghra Formation, which may coincide with the Early Miocene delta which received terrigenous material by river waters (Issawi et al. 1999), to decrease to about 0.6% in the northern section (west El Qara section).

Planktonic Foraminifera

The fauna in the lower unit of the Moghra Formation at west El Qara and El Arag sections displays a moderately high species diversity and abundance. The assemblage is dominated by *Globigerina ciperoensis*, *Gg. praebulloides, Gg. angustiumbilicata, Gg. venezuelana, Globigerinoides* cf. *bisphericus, Gs. immaturus, Gs. quadrilobatus, Gs. sicanus, Gs. trilobus, Globoquadrina dehiscens*, and *Globorotalia obesa.*

The fauna in the middle unit of the Moghra Formation at west El Qara and El Arag sections has a low species diversity and moderate abundance. Assemblages are dominated by *Globigerina* sp., *Gg. ciperoensis*, *Gg. praebulloides*, *Globigerinoides* cf. *bisphericus, Gs. immaturus*, and *Gs. trilobus.* No planktonic foraminifera were found in the upper unit of the Moghra Formation.

Benthic Foraminifera

The fauna in the lower unit of the Moghra Formation at west El Qara and El Arag sections exhibits a high diversity and high abundance. The assemblage is dominated by *Ammonia* sp., *A. beccarii, Cancris* sp., *Cibicidoides floridana, Cibicides* sp., *C. lobatulus, Elphidium* cf. *advenum*, *E. crispum, Eponides* sp., *Nonion* sp., *N. boueanus, Biloculinella elongata*, *Quinqueloculina seminula, Textularia agglutinans*, *Nonionella* sp., *Archaias* sp., *Lagena striata*, and *Discorbis* sp. In contrast, the fauna in the middle unit of the Moghra Formation at west El Qara and El Arag sections has a low species diversity and low abundance.

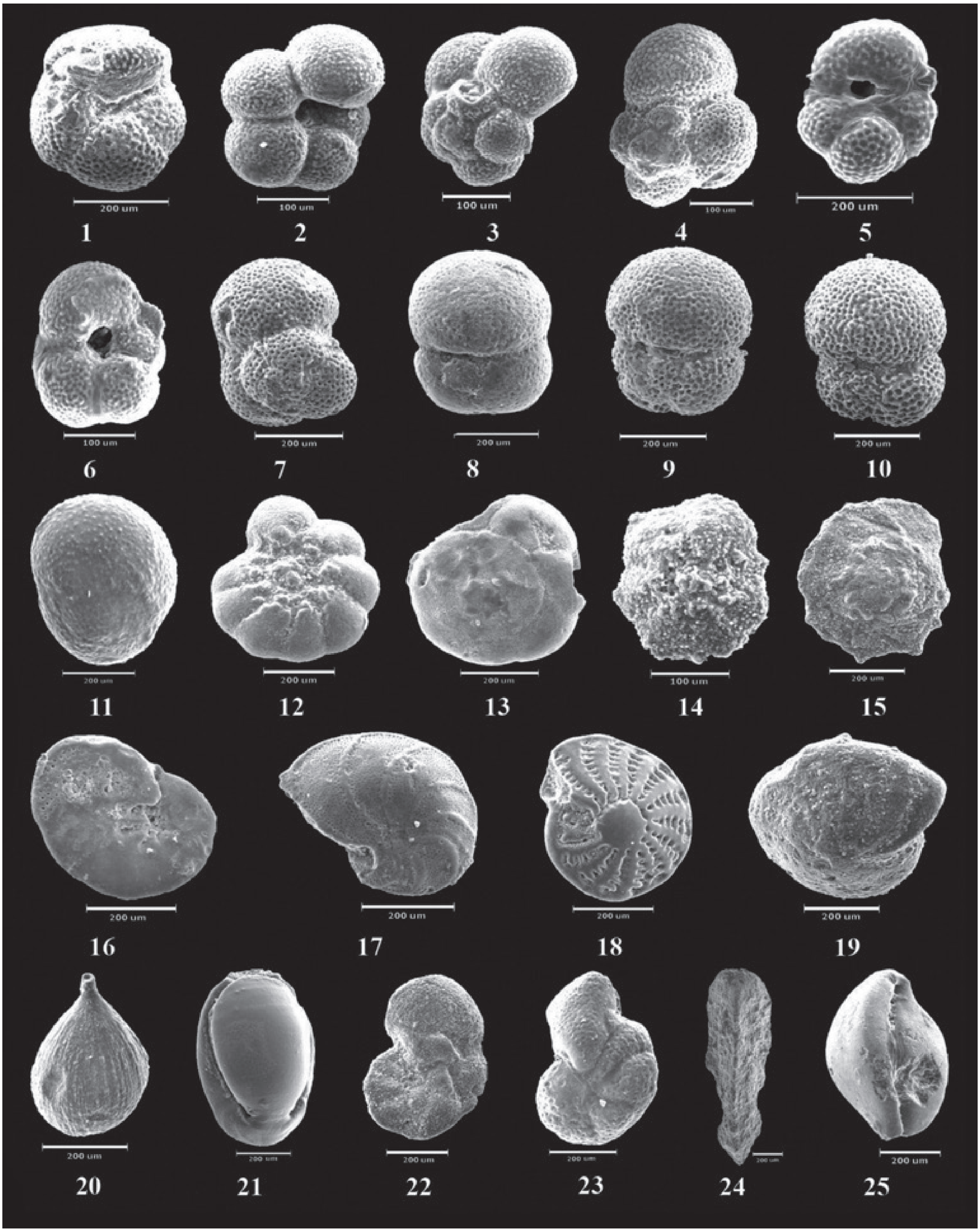
Discussion

Source of TOC

TOC recorded in the study area ranges from 0.6-1.8% in the Moghra Formation. The geographic distribution of TOC shows that its values are higher towards the south, which probably reflects larger influx of terrestrial organic carbon from several major rivers draining into the Mediterranean Sea during the Early Miocene.

During the Early Miocene the surface-water circulation was dominated by the southward flow of rivers waters, with little northward penetration of Mediterranean surface waters. This outflow of surface freshwater formed a low salinity lid, which enhanced the vertical stratification, and prevented vertical mixing and thus producing bottom waters very low in oxygen in isolated basins. To maintain this low salinity lid during the rising tempera-

Plate 1. 1. *Globoquadrina dehiscens* Chapman. Spiral view; sample no. Q35, Moghra Formation (Early Miocene), El Qara section. 2-3. *Globigerina ciperoensis* Boli. 2. Umbilical view. 3. Spiral view; sample no. Q45, Moghra Formation (Early Miocene), El Qara section. 4-5. *Globigerina praebulloides* Blow. 4. Umbilical view. 5. Spiral view; sample no. Q37, Moghra Formation (Early Miocene), El Qara section. 6. *Globigerina angustiumbilicata* Boli. Umbilical view; sample no. Q35, Moghra Formation (Early Miocene), El Qara section. 7. *Globigerinoides quadrilobatus* d'Orbigny. Spiral view; sample no. Q35, Moghra Formation (Early Miocene), El Qara section. 8. *Globigerinoides* sp. Spiral view; sample no. Q37, Moghra Formation (Early Miocene), El Qara section. 9-10. *Globigerinoides trilobus* Reuss. 9. Ventral view. 10. Dorsal view; sample no. A67, Moghra Formation (Early Miocene), El Arag section. 11. *Globigerinoides* cf. *bisphericus* Todd. Spiral view; sample no. Q43, Moghra Formation (Early Miocene), El Qara section. 12-13. *Ammonia beccarii* Linné. 12. Umbilical view. 13. Spiral view; sample no. A60, Moghra Formation, El Arag section. 14-15. *Pararotalia aculeata* d'Orbigny. 14. Umbilical view. 15. Spiral view; sample no. A63, Moghra Formation (Early Miocene), El Arag section. 16 & 17. *Cibicides lobatulus* Walker & Jacob. 16. Umbilical view. 17. Spiral view; sample no. Q37, Moghra Formation (Early Miocene), El Qara section. 18. *Elphidium crispum* Linné. Spiral view; sample no. S29, Marmarica Formation (Middle Miocene), Siwa section. 19. *Elphidium advenum* Chushman. Spiral view; sample no. Q37, Moghra Formation (Early Miocene), El Qara section. 20. *Lagena striata* d'Orbigny. Ventral view; sample no. A67, Moghra Formation (Early Miocene), El Arag section. 21. *Biloculinella elongata* D' Orbigny. Ventral view; sample no. S3, Marmarica Formation (Middle Miocene), Siwa section. 22-23. *Cibicidoides* sp. Spiral view; sample no. Q35, Moghra Formation (Early Miocene), El Qara section. 24. *Tritaxia* sp. Ventral view; sample no. S40, Marmarica Formation (Middle Miocene), Siwa section. 25. *Triloculina* sp. Umbilical view, sample no. S40, Marmarica Formation (Middle Miocene), Siwa section.



tures of the mid-Miocene warming, there must also have been an increase in the humidity of the region.

Palaeoecology

Detailed interpretation of the palaeoecology of the study area is based on the stratigraphic distribution of the foraminiferal fauna (Text-figs. 2, 5). Faunal composition and relative abundance have been used to establish faunal assemblages, which characterise different localities. These assemblages are then compared with already known depth assemblages (Norton 1930; Phleger 1960; Lipps et al. 1979; Murray 1973, 1991) in order to arrange them along a depth gradient.

Lower unit (unit I)

At the El Qara section, the lower unit of the Moghra Formation is characterized by the following benthic and planktonic foraminiferal assemblage; *Ammonia, Lagena,* *Cancris*, *Cibicidoides, Cibicides, Elphidium*, *Entalophora, Eponides*, *Nonion*, *Biloculinella*, *Quinqueloculina, Archaias, Globigerina, Globigerinoides, Globoquadrina, Globorotalia*, and *Sphaeroidinellopsis*. The percentage of Miliolidae (12%) and a distinct presence of planktonic foraminifera indicate more open marine conditions (NORTON 1930; CHERIF 1972). Porcellaneous taxa (e.g. *Miliolina*) usually represent <20% of assemblages in shelf seas that are dominated by hyaline foraminifera (MURRAY 1991).

At the El Arag section, the benthic and planktonic foraminiferal assemblage is characterized by *Ammonia, Cibicides, Elphidium*, *Nonionella, Quinqueloculina, Textularia, Discorbis, Globigerina*, and *Globigerinoides*. The fauna of this section is rich in coiled hyaline benthic foraminifera, and the sudden appearance of planktonic foraminifera (*Globigerina* and *Globigerinoides*). The benthic elements suggest shallow marine conditions (inner neritic), but the appearance of a comparatively varied assemblage of planktonic foraminifera suggests relative deepening of the sea. The relative abundance of Miliolidae together with Elphididae indicates a shallow but relatively quiet depositional environment, most likely a sheltered bay protected from the open sea, but with fully marine conditions (LOEBLICH & TAPPAN 1964).

Middle unit (unit II)

At the El Qara section, the middle unit shows a further increase in Miliolidae, accompanied by an increase in Rotaliidae (mainly *Ammonia beccarii*). The general decrease in other foraminifera indicates fluctuations in salinity towards brackish water. At the Siwa section, the low relative abundance of *Ammonia beccarii* indicates temporary brackish-water influence.

The Middle unit is inhabited by epifaunal taxa such as *Quinqueloculina* and *Elphidium*, indicating warm water conditions (MURRAY 1991), and by infaunal taxa such as *Ammonia*, which are common in sediments with highly variable mud and TOC content (MURRAY 1991). *Ammonia* is considered to tolerate chemical and thermal pollution, fertilizing products, and hydrocarbons (BERGIN et al. 2006).

Upper unit (unit III)

No planktonic foraminifera were found in the upper unit, which in the El Qara section is characterized by the presence of porcellaneous benthic foraminifera (Miliolina); the assemblage suggests warm littoral and sublittoral (CHERIF & EL-HALABY 1996). *Quinqueloculina seminula* may be epifaunal or infaunal, and dominates in lagoons and marshes (MURRAY 2006).

Benthic Foraminifera

The fauna of unit I has a comparatively high diversity and high abundance, being dominated by *Ammonia, Lagena, Cancris*, *Cibicidoides, Cibicides, Elphidium*, *Entalophora, Eponides*, *Nonion*, *Nonionella, Biloculinella*, *Quinqueloculina, Archaias*, *Textularia,* and *Discorbis*. In contrast, unit II has a low faunal diversity and generally low abundance, and the fauna is strongly dominated by *Nonion*, *Elphidium, Ammonia, Cibicides*, *Quinqueloculina*, *Biloculinella* and *Borelis*. In unit II there is an exceptional turn-over, with the entire fauna of unit I disappearing or being reduced to less than 20% of the assemblage. The low diversity and abundance of benthic foraminifera fauna within the sapropelic layers is due to anoxic bottom-water conditions during deposition of these layers prevented bioturbation. The oxygen content of the bottom waters was generally low (YAŞAR 1994).

Planktonic Foraminifera

The fauna in unit I displays moderately high species diversity and abundance. The assemblage is dominated by *Globigerina, Globigerinoides, Globoquadrina, Globorotalia*, and *Sphaeroidinellopsis*. The fauna in unit II has very low species diversity and moderately abundance. Assemblages are dominated by *Globigerina* and *Globigerinoides*. No planktonic foraminifera were found in the upper unit of the Moghra Formation (unit III). The sapropelic layers in the study area were produced by enhanced freshwater dilution, elevated productivity, shoaling of the pycnocline between intermediate and surface waters, and stagnation of the subsurface circulation. Under these conditions, some species to shifted to other habitats (ROHLING et al. 2004).

Conclusions

1. Sapropelic layers are identified in the northern Western Desert of Egypt at Siwa, El Qara and El Arag oases as olive or greyish, weakly laminated muds and shales. They are characterized by 0.6-1.8% TOC.
2. The benthic foraminiferal fauna in the sapropelic layers of unit I of the Moghra Formation is characterized by a low diversity assemblage distinctive of high nutrient availability, and low oxygen conditions. However, the presence of benthic foraminifera in sapropelic layers suggests that the surface sediments during the deposition of these layers were oxic.
3. Brackish waters were recorded in late Early Miocene at the El Qara section, where the middle unit of the Moghra Formation shows an increase in Miliolidae, accompanied by an increase in Rotaliidae (mainly *Ammonia beccarii*), indicating fluctuations in salinity towards brackish-water.
4. Sapropelic layers in the area under study were deposited as a result of stratification of the water column and stagnation of bottom waters resulting from increased inflow of freshwaters. ISSAWI et al. (1999) argued that the transgression along the Mediterranean coast rapidly covered the northern Western Desert, the present Nile Delta and the

coastal area of Sinai. The Oligocene rivers moved northward and an Early Miocene delta developed at the Moghra Oasis of the Western Desert.

5. Rossignol-Strick (1985) proposed that the sapropelic layer resulted from River Nile floods following increased monsoonal summer precipitation in tropical eastern Africa. Moreover, Rohling & Hilgen (1991) argued that an increased humidity is necessary to maintain a low salinity surface layer and that the sapropelic layers formed during precessional minima, which intensified summer monsoon circulation in the western Indian Ocean, as well as during enhanced runoff from the River Nile and other eastern Mediterranean rivers.
6. The Miocene deposits in the northern Western Desert are represented by deltaic deposits of the Moghra Formation (Aquitanian-Burdigalian), where the clay fraction of the sapropelic layers of unit I and unit II of the Moghra Formation is characterized by a noticeable decrease in smectite and kaolinite and an increase in illite and chlorite, reflecting increased runoff from rivers (Yaşar 1994), which flowed directly into the Western Desert of Egypt.

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