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Larger benthic foraminiferal turnover across the Eocene–Oligocene transition at Siwa Oasis, Western Desert, Egypt

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ABSTRACT

In the Eocene part of the Siwa Oasis, the larger foraminifera are represented by the genera *Nummulites*, *Arxina, Operculina, Sphaerogypsina, Asterocyclina, Grzybowskia, Silvestriella, Gaziryina* and *Discocyclina* in order of abundance. *Operculina* continues up to the early Oligocene as modern representatives in tropical regions, while the other genera became extinct. Nevertheless, the most common larger foraminiferal genus *Lepidocyclina* (*Nephrolepidina*) appears only in the lowermost Oligocene.

In spite of the Eocene–Oligocene (E/O) transition is thought to have been attended by major continental cooling at northern middle and high latitudes, we discover that at the Siwa Oasis, there is a clear warming trend from the late Eocene (extinction level of *Nummulites*, *Sphaerogypsina, Asterocyclina, Grzybowskia*, *Silvestriella* and *Discocyclina*) to the early Oligocene is observed due to the high abundance of *Operculina* and occurrence of kaolinite and gypsiferous shale deposits in both Qatrani and El Qara formations (Oligocene) at this transition. The El Qara Formation is a new rock unit proposed herein for the Oligocene (Rupelian age) in the first time.

Several episodes of volcanic activity occurred in Egypt during the Cenozoic. Mid Tertiary volcanicity was widespread and a number of successive volcanic pulses are starting in the late Eocene. The release of mantle CO_2 from this very active volcanic episode may have in fact directly caused the warm Eocene–Oligocene greenhouse climate effect.

1. Introduction

The Eocene–Oligocene climate transition (EOCT), is often cited as the most important interval of climate change during the Cenozoic because it heralds the switch from the warmer, equable, global greenhouse climates of the late Mesozoic and early Paleogene to the cooler, more seasonal, icehouse climates. Marine proxy data suggest significant cooling of mid- to high-latitude ocean temperatures (5–6 °C) over a short interval during the earliest Oligocene, beginning at about 33.7 Ma (Zachos et al., 2008; Liu et al., 2009; Miller et al., 2009). This cooling coincided with the onset of continental glaciation in Antarctica and with changes in patterns of ocean circulation. Changes in the marine realm had a profound effect on invertebrates, causing major faunal turnover (Dockery and Lozouet, 2003; Nesbitt, 2003; Pearson et al., 2008). In general there is a change from semi-humid, forested conditions in the latest Eocene to progressively more arid and more open conditions in the earliest Oligocene.

The palaeoclimatic event at the Eocene–Oligocene transition has attracted the attention of many paleontologists, palaeobotanists and researchers of palaeoenvironmental science (e.g., Molina et al., 1986; Collinson, 1992; Collinson et al., 2010; Kvaček, 2010 and Teodoridis et al., 2012). In general, the pronounced cooling in this time interval (e.g., Zanazzi et al., 2007; Hren et al., 2013) induced also changes in benthic foraminifera, although this event manifested variously in the mid-northern latitudes (Akhmetiev et al., 2009). During Late Eocene/Early Oligocene time, a global cooling caused biotic turnovers in many groups, both in oceanic and terrestrial domains (Coxall and Pearson, 2007).

Numerous studies have dealt with the climatic and biotic changes across the E/O transition (Pomerol and Premoli Silva, 1986; Premoli Silva et al., 1988; Prothero and Berggren, 1992; Molina et al., 1993, 2006; Thomas and Shackleton, 1996; Spezzaferri et al., 2002; Boukhary et al., 2012; Muftah and Boukhary, 2013) to elucidate the environmental effects of this crisis as well as to determine possible cause of climate change and extinctions (Keller, 1986; Keller et al., 1987; Montanari, 1990; Molina et al., 2004, 2006).

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The fundamental aims of this study are to investigate the possible causes of the Eocene/Oligocene (E/O) boundary turnover by analyzing patterns of benthic larger foraminiferal changes across the E/O of the Siwa Oasis (Western Desert, Egypt) to seek correlations between two sections namely; El Arag and El Qara (Fig. 1). This has been done to evaluate evidence for or against two rival hypotheses; (1) the meteorite impacts, and (2) possible climatic changes (warming/cooling).

1.1. Meteorite impacts

Molina et al. (1993) suggested that there were three late Eocene impact events within about 1 Ma (34.7–35.7 myr) in the middle Priabonian, and concluded that major species extinctions did not coincide with those impact events. Molina et al. (2004) discovered one major and two minor Ni-rich spinel anomalies at Fuente Caldera section, southern Spain, which are indicative of one or possibly several meteorite impacts and thus permit research into the possibility of a cause-effect relationship between late Eocene meteorite impacts and the extinction of foraminifera.

More impact evidence was discovered in upper Eocene sediments (Keller et al., 1987), including iridium anomalies (Montanari et al., 1993), shocked quartz (Glass and Wu, 1993; Clymer et al., 1996), and Ni-rich spinel (Pierrard et al., 1998; Molina et al., 2004). Moreover, three impact craters were found at Popigai (100 km), northern Siberia (Bottomley et al., 1993), Chesapeake Bay (90 km) and Toms Canyon (20 km) on the North American continental shelf (Koeberl et al., 1996; Poag and Pope, 1998).

In contrast the catastrophic mass extinction event at the Cretaceous/Tertiary boundary, meteorite impact in the late Eocene did not cause the extinction of foraminifera, probably because the impact were relatively smaller, as suggested by the size of the coeval craters (Molina et al., 2006).

Molina et al. (2006) argued that at Fuente Caldera, southern Spain, the impact did not occur at a time of planktonic or benthic foraminiferal extinction event, and the Late Eocene meteorite impacts did thus not cause extinction of foraminifera. The most plausible cause of the Eocene/Oligocene boundary extinctions is the significant cooling, which generated glaciation in Antarctica and eliminated most of the warm and surface-dwelling foraminifera.

1.2. Possible climatic changes

1.2.1. Warming

At the onset of the Eocene, during a period of ca 100–150 kyr, the high latitudes and global deep waters experienced a 6–8 °C warming (Kennett and Stott, 1991). This warming event, referred to the Initial Eocene Thermal Maximum (IETM) is probably represents the warmest period on Earth during the Cenozoic. The warming coincides with global mass extinctions of 30–50% of the deep-sea benthic foraminiferal species (Ross, 1974; Tjalsma and Lohmann, 1983; Miller et al., 1987; Kennett and Stott, 1991; Thomas and Shackleton, 1996; Thomas et al., 2000). The prominent heating of the high latitudes has been explained in terms of an extreme green house event (Dickens et al., 1997), alternatively, as a shift in deep-water formation from high latitudes to the net evaporation zones at midlatitudes and increased poleward heat transport (Kennett and Stott, 1991; Thomas and Shackleton, 1996).

The transition from the global warmth of the early Eocene "greenhouse" climate to the glaciated state of the Oligocene is

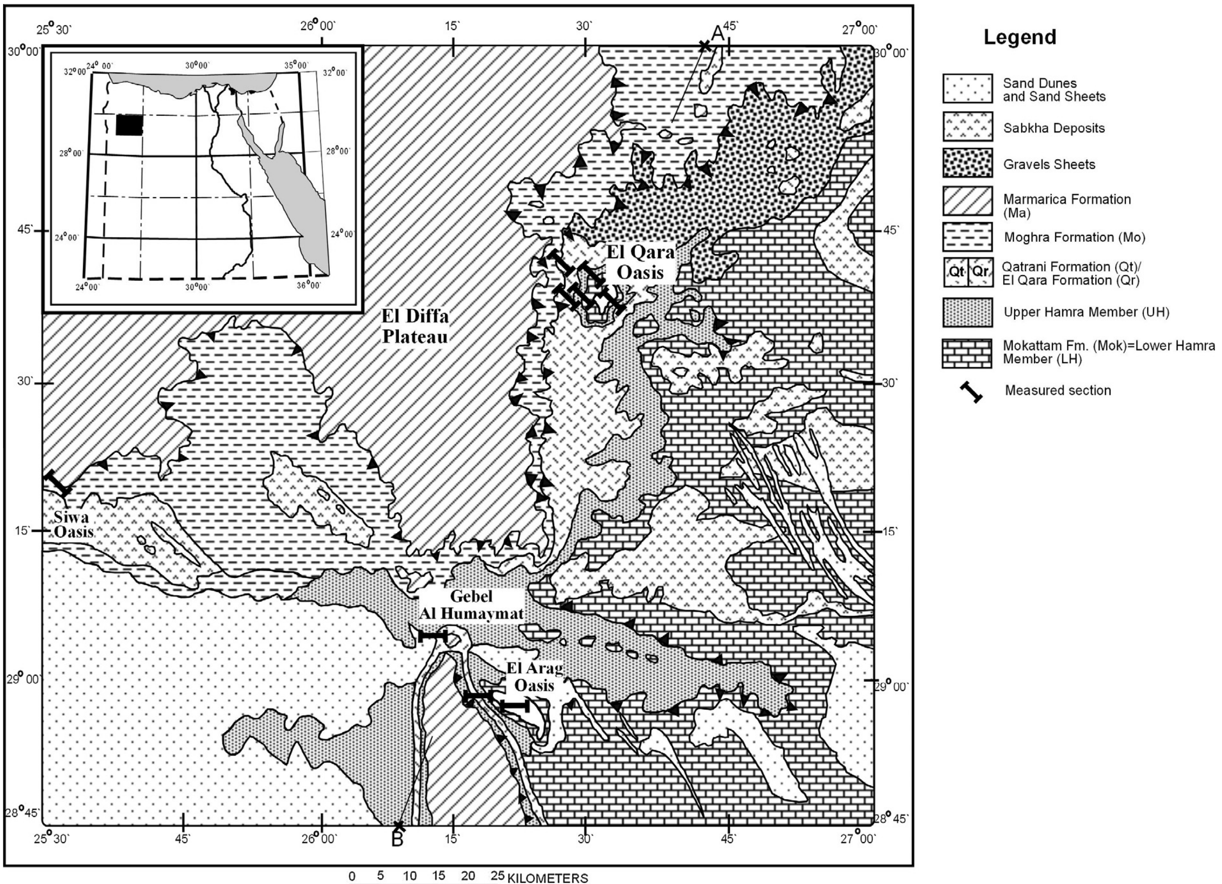

Fig. 1. Geological map of Siwa–El Qara stretch North Western Desert of Egypt.

one of the most significant changes in the Cenozoic evolution of the Earth's climate (Zachos et al., 2001; Tripati et al., 2005). Hren et al. (2013) studied the continental sediments of the Solent Group in the Hampshire Basin (Isle of Wight, United Kingdom). They suggest that the transition from the "greenhouse" state of the Late Eocene to the "icehouse" conditions of the Oligocene 34–33.5 Ma was triggered by a reduction of atmospheric $p\mathrm{CO}_2$ that enabled the rapid buildup of a permanent ice sheet on the Antarctic continent. Marine records show that the drop in $p\mathrm{CO}_2$ during this interval was accompanied by a significant decline in high-latitude sea surface and deep ocean temperature and enhanced seasonality in middle and high latitudes.

1.2.2. Cooling

One of the biggest cooling events a switch from so-called "greenhouse" to "icehouse" conditions occurred across the Eocene/Oligocene transition ca. 33.5 Ma (Miller et al., 1987). The Eocene/Oligocene (E/O) transition is thought to have been attended by major continental cooling at northern middle and high latitudes and the development of an Antarctic ice cap approximately half its present size (Miller et al., 1987; Zachos et al., 1994, 2001). A popular view of the causes of Eocene–Oligocene transition cooling ascribes a singular role to the development of the Antarctic Circumpolar Current via separation of Tasmania and South America from Antarctica and consequent reorganization of the world's ocean currents (Kennett, 1977).

During the E/O transition spanning from the late middle Eocene to early Oligocene, global temperatures cooled more than any time since the Mesozoic leading to the formation of the first Antarctic ice sheets. During this time a circum-Antarctic circulation pattern was established as Australia separated from Antarctica and the oceans changed from a thermospheric to thermohaline circulation as a result of Antarctic glaciations (Kennett, 1977, 1980). Associated with these climatic and oceanic circulation changes are major waves of extinctions among terrestrial and marine organisms (Prothero and Berggren, 1992).

The cause of cooling remains controversial, where Vonhof et al. (2000) suggested that the cooling might have been accelerated by the meteorite impacts at 35.5 Ma. The cooling might have been triggered by the opening of the Drake Passage (Livermore et al., 2005), other suggested that the opening of Southern Ocean gateways alone could not have caused major changes in meridional heat transport and show that abrupt cooling could have resulted from a steady decline in atmospheric CO_2 (DeConto and Pollard, 2003; Huber et al., 2004; Tripati et al., 2005).

2. Location and Stratigraphy

Siwa Depression (north Western Desert of Egypt) lies between latitudes 29°00′–29°30′N, and longitudes 25°16′–26°6′E. At Siwa Oasis Larger foraminifera are major sediment constituents in shallow water carbonates of upper Eocene/Oligocene (E/O) sequences associated with bryozoa, algae, bivalves, echinoids, gastropods and corals at Siwa Oasis.

Due to the poor preservation of some fossils and reworking of index fossils in the area under study, the boundaries between different biostratigraphic zones have great uncertainties and unable us for high-resolution correlation. Our correlation based on larger foraminifera (*Nummulites*, *Operculina*, *Arxina, Gaziryina, Sphaerogypsina*, *Asterocyclina*, *Grzybowskia*, *Silvestriella* and *Lepidocyclina*) and lithology may be highly justified, considering that the two sections (El Arag and El Qara of the Siwa Oasis, Western Desert) lie only170 km apart (Fig. 1).

The samples studied herein are a continuous record of the Lower Eocene to Oligocene, an interval that records one of the most important Cenozoic climatic transitions. The collected successions are preferable to the Mokattam Formation of middle Eocene (late Lutetian), Upper Hamra Member of upper Eocene (Priabonian) and Qatrani/El Qara Formation of Oligocene (Rupelian).

The Mokattam Formation of Zittel (1883) is recorded at El Arag section (90.27 m) and El Qara section (19.10 m) its top unconformably underlies the Upper Hamra Member of Said and Issawi (1964). This formation is composed of white Nummulitic limestone chalky in place with yellow dolomitic at the upper part. The larger foraminifera identified from this formation are represented by *Nummulites pachoi*, *N. praebullatus*, *N.* group *bullatus*, Precursors of group *N. gizehensis*, *N.* cf. *discorbinus*, *N.* aff. *schwageri*, *N.* cf. *gizehensis*, *Gaziryina* aff. *Pulchellus*, *Arxina schwageri*, *Sphaerogypsina globula* and *Discocyclina* sp. The analysis of the fossil content indicates this formation belong to the middle Eocene (late Lutetian) (Figs. 2 and 3).

The upper part of the Eocene rocks at El Arag section (about 5 m thick) and at El Qara section (about 21.50 m thick) assigned to Priabonian age of the Upper Hamra Member and overlies with seeming unconformity surface of the Mokattam Formation (late Lutetian) representing by paleosol bed. These successions are composed of light red to brown, hard and fossiliferous reworked limestones. The larger benthic foraminifera collected from this member represented by *Nummulites fabianii, Gaziryina pulchellus, Silvestriella tetraedra* and *Grzybowskia* sp. (Plate 1). The analysis of the fossil content indicates that this member belongs to the upper Eocene (Priabonian).

The Qatrani Formation (Oligocene) of Beadnell (1905) unconformably overlies the Upper Hamra Member and conformably underlies the Moghra Formation (early Miocene) of Marzouk (1969). This formation is only recorded at El Arag section and it attains about 24.5 m thick, which composed of yellow to greenish yellow sandstone, calcareous sandstone with quartz pebbles intercalation. The Qatrani Formation is a rule remarkably barren of organic remains. It is characterized by the quantities of silicified wood, vertebrate bone fragments and few fragments of Mollusca.

At El Qara section, the El Qara Formation is a new rock unit proposed herein for the Oligocene (Rupelian age) in the first time, where the El Qara Formation represented by gypsiferous shales, which considered to have been deposited in back-reef lagoonal conditions. The top of this formation is unconformably underlies the Moghra Formation (early Miocene). It attains about 45.50 m thick and consists mainly of cross-bedded limestone beds occurred at the base and the top have larger foraminifera represented by *Operculina* sp. and *Lepidocyclina* (*Nephrolepidina*) *nipponica,* which indicates this formation belong to the early Oligocene (Rupelian). The sediments of the El Qara Formation contain mudstone (koalinite) and gypsiferous shale intercalation in the cross-bedded limestone of the Oligocene age.

3. Volcanic activity

Several episodes of volcanic activity occurred in Egypt during the Cenozoic (Said, 1981). The earliest one was of Paleocene age and represented the continuation of the extensive late Cretaceous igneous activity. Mid Tertiary volcanicity was widespread and a number of successive volcanic pulses are starting in the late Eocene with subsequent extensional phases ranging from late Oligocene to middle Miocene. Basaltic extrusive covers a large area beneath the Nile Delta and the adjacent parts of the Western Desert (Bayoumi and Sabri, 1971; Said, 1981; William and Small, 1984).

In the southern parts of the Western Desert, some Tertiary basaltic occurrences are sparsely distributed. In places, they are associated with minor occurrences of acid to alkaline rocks (Meneisy and Abdel Aal, 1984).

During the late Eocene, a shallowing of the Tethys took place and the Oligocene was marked by emergence. Volcanics developed

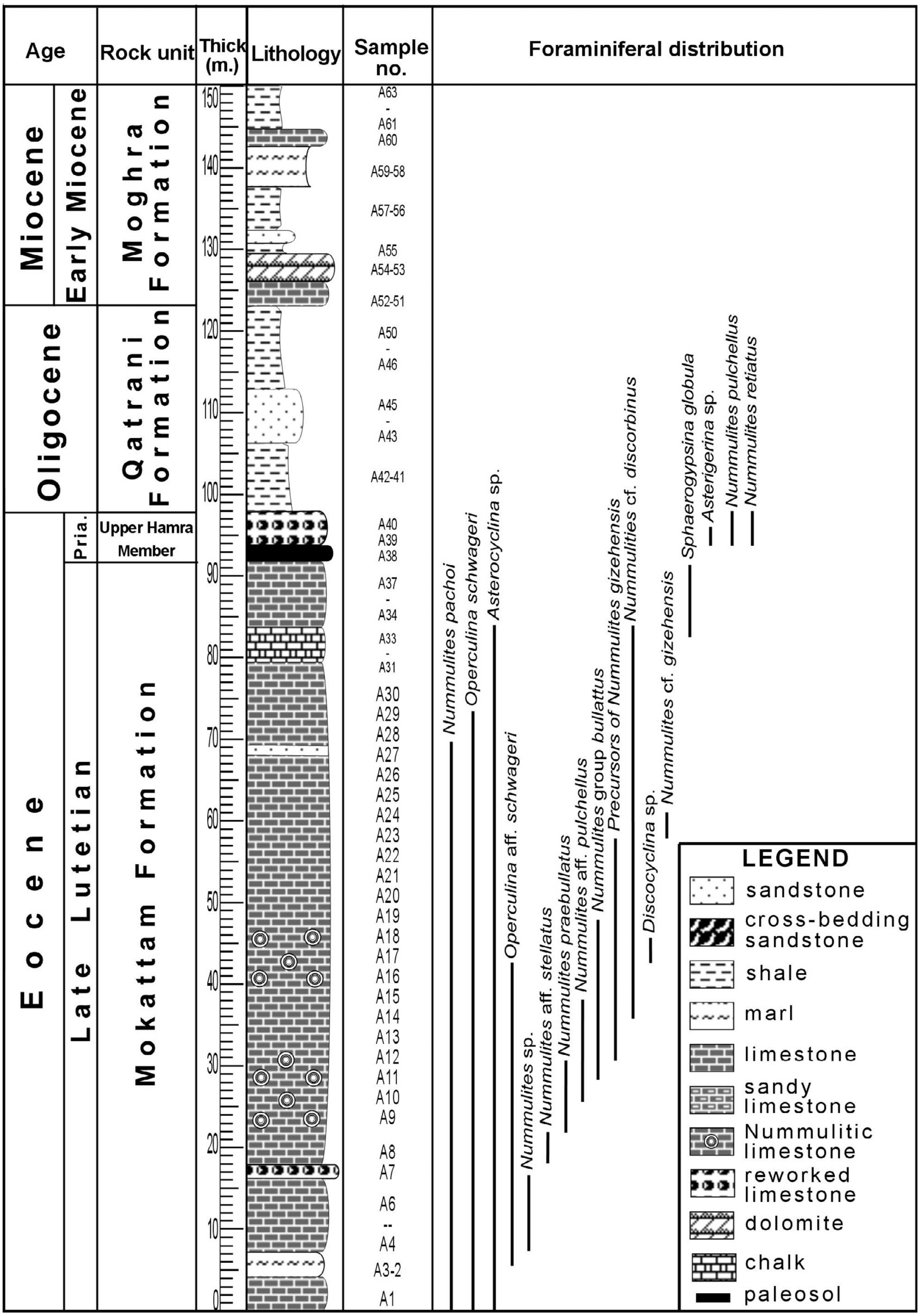

Fig. 2. Stratigraphic range chart of larger benthic foraminiferal species at El Arag section.

along the fracture systems associated with these tectonically-controlled movements (Meneisy and Kreuzer (1974).

The release of mantle CO_2 from this very active volcanic episode may have in fact directly caused the warm Eocene–Oligocene greenhouse climate. Thus, the study of this transition paleoclimate and paleoceanography provides insight into a natural climatic experiment, when a large amount of CO_2 was released into the atmosphere.

4. Results

4.1. Larger benthic foraminifera

In the Eocene part of the area under consideration, the larger foraminifera are represented by the genera *Nummulites*, *Operculina*, *Arxina*, *Gaziryina*, *Sphaerogypsina*, *Asterocyclina*, *Silvestriella*, *Grzybowskia* and *Discocyclina* in order of abundance.

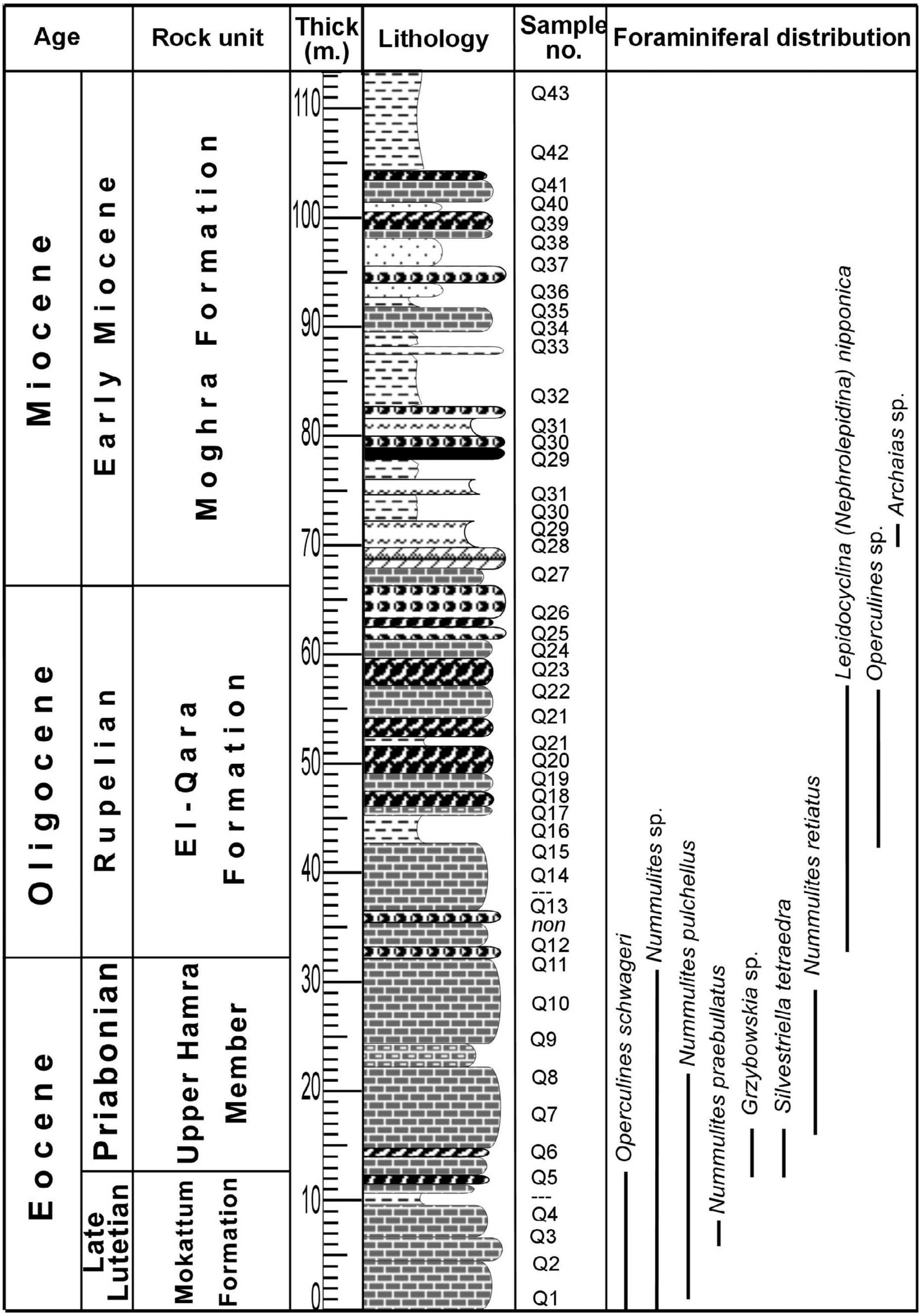

Fig. 3. Stratigraphic range chart of larger benthic foraminiferal species at El Qara section.

Operculina continues up to the early Oligocene, while the other genera became extinct. Nevertheless, the most common larger foraminiferal genus *Lepidocyclina* (*Nephrolepidina*) appears only in the lowermost Oligocene.

Among the larger foraminifera recorded in this area; *Nummulites*, *Lepidocyclina* (*Nephrolepidina*), *Sphaerogypsina*, *Asterocyclina*, *Silvestriella*, *Grzybowskia* and *Discocyclina* are extinct taxa but *Operculina* has modern representatives in tropical regions (Kumar and Saraswati, 1997). The dominance of Nummulitidae sharply declines in the overlying subtidal sequences of the late Lutetian and Priabonian age (Eocene). Operculines are the only representatives of this family to continue in this environment (Hottinger, 1983).

The dominant taxa in the El Qara Formation (Oligocene) include *Lepidocyclina* (*Nephrolepidina*), and *Operculina*, which assigned to eurytopic taxa (Hottinger, 1983, 1998; Murray, 1991) inhabiting lagoon to shallow subtidal environment and low to high energy conditions (Kumar and Saraswati, 1997), and the temperatures in

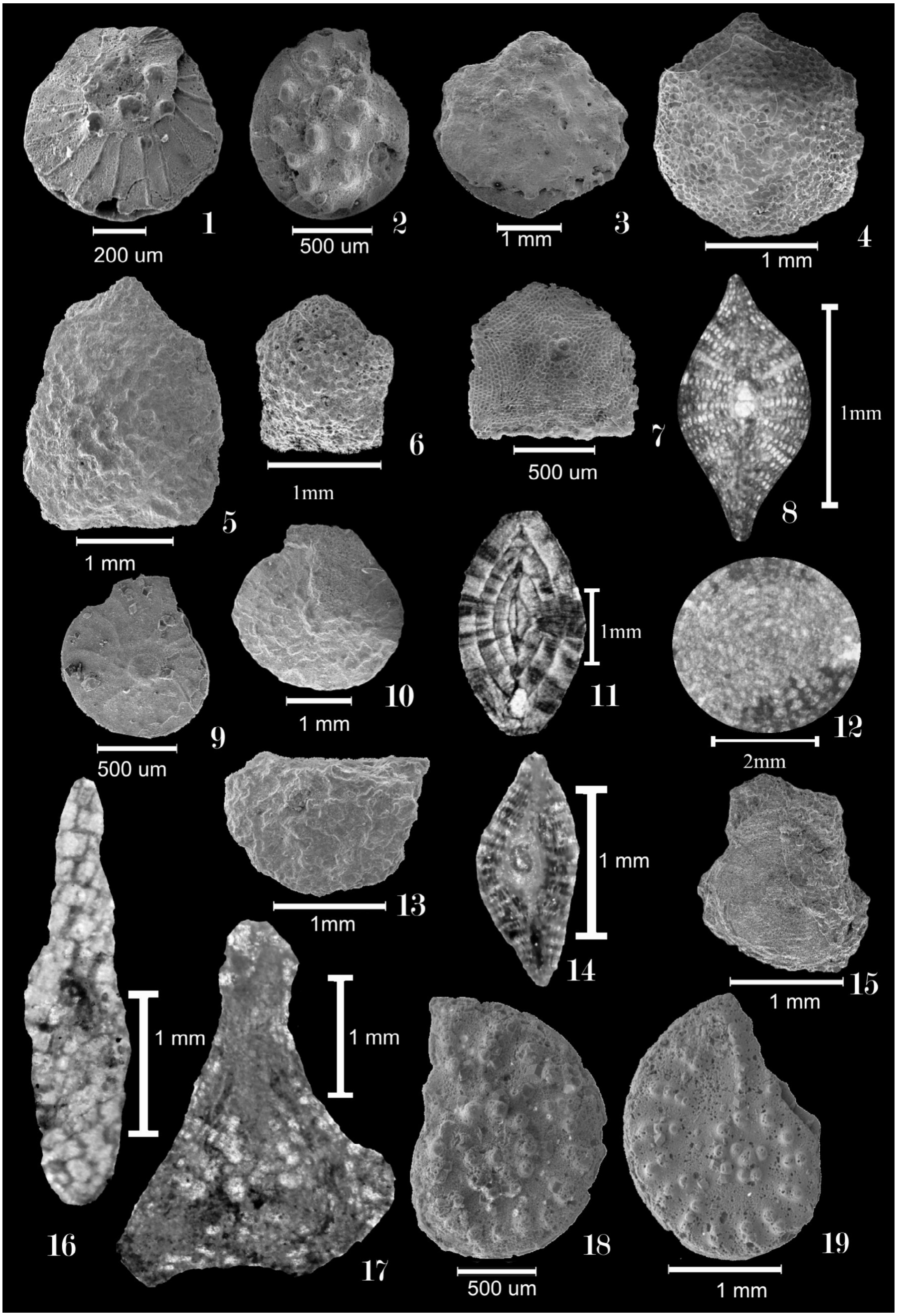

Plate 1. (1) *Nummulites praebullatus* SCHAUB, external view; sample No. A9, Mokattam Formation (Late Lutetian), El Arag section. (2) and (3). *Nummulites* aff. *bullatus* AZZAROLI, (2) and (3), external view; sample No. A18, Mokattam Formation (Late Lutetian), El Arag section. (4)–(8) *Asterocyclina stellata* D' ARCHIAC, (4)–(6), external view, (7), equatorial section and (8), axial section; samples No. A5, A6, Mokattam Formation (Late Lutetian), El Arag section. (9). *Gaziryina* aff. *pulchellus* HANTKEN in DE LA HARPE, external view; sample No. A14, Mokattam Formation (Late Lutetian), El Arag section. (10) and (11) *Nummulites fabianii* PREVER, (10), external view and (11), thin section; sample No. A39, El Arag Formation (Priabonian), El Arag section. (12) *Sphaerogypsina globula* REUSS, thin section; sample No. A34, Mokattam Formation (Late Lutetian), El Arag section, Western Desert. (13), (14) *Lepidocyclina* (*Nephrolepidina*) *nipponica* HANZAWA, (13), external view; sample No. Q10 and (14), thin section; sample Q26, El Qara Formation (Rupelian), El Qara section. (15) *Archaias* sp., external view; sample No. Q24, Moghra Formation (Early Miocene), El Qara section. (16) *Grzybowskia* sp., thin section view; sample No. Q10, El Arag Formation (Priabonian), West of El Qara Village Section. (17) *Silvestriella tetraedra* GÜMBEL, thin section view; sample No. Q11, El Arag Formation (Priabonian), West of El Qara Village Section. (18) and (19) *Arxina schwageri* SILVESTRI, (18) and (19) external views, sample No. A29, Mokattam Formation (Late Lutetian), El Arag section.

excess of 20–22 °C for reproduction (Murray, 1991; Hottinger, 1998).

4.2. Lithological data

The Mokattam Formation (late Lutetian) is composed of white Nummulitic limestones and coral patches chalky in place. Patch reefs are commonly found in recent shelf lagoons as in the Caribbean (Tucker, 1985). The sediments of the Mokattam Formation appear to have formed in back-reef lagoons.

Nevertheless, the Upper Hamra Member is composed of light red to brown, hard and Nummulitic reworked limestones and overlies with seeming unconformity surface of the Mokattam Formation (late Lutetian) representing by paleosol bed. Petrographic data suggest that these soils of the Hamra Member are excellent indicators for a warm semiarid climate (Estebanm and Klappa, 1983; Eichenseer and Betzler, 1987). Paleosol records from the Hampshire Basin suggest minimal temperature change but an increase in precipitation across the Eocene Oligocene transition (Sheldon, 2009).

Reworked foraminiferal tests are found in cross-bedded limestone of the Oligocene sediments (El Qara Formation) at El Qara section which is inferred to have been deposited in tidal channels. Moreover, the presence of mudstone (koalinite) and gypsiferous shale intercalation in the cross-bedded limestone of the Oligocene sediments has been interpreted by some authors to reflect a shift towards warm humid conditions, based on kaolinite forms in soils of humid, tropical environments (Knox, 1998; Gawenda, 1999; Gawenda et al., 1999).

However, kaolinite deposition in today's ocean also occurs in coastal regions off semiarid or arid regions where kaolinites from ancient wet periods are being eroded (Chamley, 1989; Thiry, 2000). A strong evidence for semiarid conditions in El Qara and El Arag sections during the IETM event is the occurrence of evaporate deposits in both Qatrani and El Qara formations. The El Qara Formation (Oligocene) represented by gypsiferous shales, which considered to have been deposited in back-reef lagoonal conditions (Saraswati and Banerji, 1984).

5. Summary and conclusion

At the studied area there is a clear warming trend from the late Eocene (extinction level of *Nummulites*, *Sphaerogypsina, Asterocyclina, Grzybowskia*, *Silvestriella* and *Discocyclina*) to the early Oligocene is observed due to the high abundance of *Operculina* and occurrence of kaolinite and gypsiferous shale deposits in both Qatrani and El Qara formations (Oligocene) at this transition.

The larger foraminifera recorded in the E/O transition; *Nummulites*, *Gaziryina*, *Lepidocyclina* (*Nephrolepidina*), *Sphaerogypsina*, *Asterocyclina*, *Silvestriella*, *Grzybowskia* and *Discocyclina* are extinct taxa but *Operculina* has modern representatives in tropical regions.

The presence of mudstone (koalinite) and gypsiferous shale intercalation in the cross-bedded limestone of the Oligocene sediments (Rupelian) has been interpreted by some authors to reflect a shift towards warm humid conditions, based on kaolinite forms in soils of humid, tropical environments.

A strong evidence for semiarid conditions in El Qara and El Arag sections during the IETM event is the occurrence of evaporate deposits in both Qatrani and El Qara formations (Oligocene). The El Qara Formation (Rupelian) represented by gypsiferous shales, which considered to have been deposited in back-reef lagoonal conditions.

The Upper Hamra Member (Priabonian) overlies with seeming unconformity surface of the Mokattam Formation (late Lutetian) representing by paleosol bed, which indicators a warm semiarid climate.

The El Qara Formation is a new rock unit proposed herein for the Oligocene (Rupelian age) in the first time, where the El Qara Formation represented by gypsiferous shales. The top of this formation is unconformably underlies the Moghra Formation (early Miocene). It attains about 45.50 m thick and consists mainly of cross-bedded limestone beds.

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