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# New microplanktonic biostratigraphy and depositional sequences across the Middle–Late Eocene and Oligocene boundaries in eastern Jordan

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## ABSTRACT

The first detailed calcareous nannofossil and planktonic foraminiferal biostratigraphic and integrated lithofacies analyses of the Eocene–Oligocene transition at the Qa' Faydat ad Dahikiya area in the Eastern Desert of Jordan, on the border with Saudi Arabia, is presented. Three calcareous nannofossil zones namely: *Discoaster saipanensis* (NP17), *Chiasmolithus oamaruensis* (NP18) and *Ericsonia subdisticha* (NP21), and three planktonic foraminiferal zones: upper part of *Truncorotaloides rohri* (E13), *Globigerinatheka semiinvoluta* (E14) and *Cassigerinella chipolensis/ Pseudohastigerina micra* (O1) are identified.

Calcareous nannofossil bioevents recorded in the present study show numerous discrepancies with the Standard biostratigraphic zonal schemes to detect the Middle/Upper Eocene boundary (e.g. the highest occurrences (HOs) of *Chiasmolithus solitus*, *C. grandis*, and lowest occurrences (LOs) of *C. oamaruensis*, *Isthmolithus recurvus* are not considered reliable markers for global correlation). The Middle/Upper Eocene boundary occurs in the current study above the extinctions of large muricate planktonic foraminifera (large *Acarinina* and *Truncorotaloides* spp.) which coincide within the equivalent calcareous nannofossil NP18 Zone. These microplanktonic bioevents seem to constitute more reliable markers for the base of the Upper Eocene in different provinces. The uppermost portion of the Middle Eocene is characterized by an observed drop in faunal content and, most likely, primarily denotes the effect of the major fall in eustatic sea level.

A major unconformity (disconformity) marked by a mineralized hardground representing a lowstand is recorded in the present study at the Eocene–Oligocene transition that reveals an unexpected ca. 2.1 Myr duration, separating Eocene (NP18/E14 zones) from Oligocene (NP21/O1 zones). Furthermore, the microfossil turnover associated with a rapid decline of the microfossil assemblages shows a distinct drop in diversity and abundance towards the Eocene/Oligocene unconformity and is associated with a sharp lithological break marked, at the base, by a mineralized hardground representing a major sequence boundary. These bioevents, depositional sequences and the depositional hiatus correlate well with different parts of the Arabian and African plates, but the magnitude of the faunal break differs from place to place as a result of intraplate deformation during the regional Oligocene regression of Neo-Tethys on the northern Arabian Plate. The presence of the Lower Oligocene shallow-marine calcareous planktonic assemblages in the study area indicate that communication between the eastern and western provinces of the western Neo-Tethys region still existed at this time.

## INTRODUCTION

The Eocene/Oligocene boundary is of worldwide stratigraphic importance because it represents a major biostratigraphical event and a change from warm to colder marine paleoenvironments during the Cenozoic Era. Many discrepancies in Paleogene microplanktonic bioevents have been noted by previous authors, which may be related to different taxonomic concepts or perhaps due to different paleoecological parameters pertaining across different paleolatitudes.

Furthermore, the Global Stratotype Section and Point (GSSP) for the Middle/Upper Eocene boundary is currently under discussion and has not been formally proposed. Consequently, there is still uncertainty concerning the definition and recognition of global geological stage and age boundaries such as the Bartonian/Priabonian boundary (Agnini et al., 2011; Wade et al., 2011; Strougo et al., 2013). In Jordan, these Middle/Upper Eocene to Lower Oligocene bioevents have not been previously discussed in detail, and this study adds new biostratigraphical and sedimentological information from a new geographic area in the Eastern Desert of Jordan. Although, there is little detailed information concerning the Upper Paleogene biostratigraphy of Jordan, previous investigations have concentrated on the vertebrate fossils (Zalmout et al., 2000; Mustafa and Zalmout, 2002); echinoid macrofossils (Zachos et al., 2008); larger foraminifera (Hamdan et al., 2013); and microplanktonic stratigraphy (Farouk et al., 2013).

The Natural Resources Authority, geological map (Al Umari sheet 3453 III, Rabba', 1997) indicates that the Middle–Upper Eocene Wadi Shallala Chalk Formation is widely distributed in the southeastern part of Qa' Faydat ad Dahikiya area, and is directly overlain by Miocene Qirma Calcareous Sandstone with the complete absence of Oligocene strata (Figure 1). In contrast (Bender, 1968, 1974) attributed a possible Oligocene age to the upper part of the Wadi Shallala Chalk Formation, which was recently distinguished by Farouk et al. (2013) as Early Rupelian Wadi El Ghadaf Formation by means of microplanktonic fauna.

A detailed microplanktonic stratigraphy needs to be undertaken in the surrounding countries, such as Saudi Arabia, following the discovery of a new Oligocene primate from Saudi Arabia by Zalmout et al. (2010). The present study provides the first detailed lithologic description and high-resolution, integrated calcareous plankton biostratigraphy and paleogeography to be carried out in the Paleogene of the Qa' Faydat ad Dahikiya area, located about 194 km southeast of Amman and 8 km northeast of the Al-Umari check-point on the border with Saudi Arabia (Figure 1a). We describe the planktonic foraminifera and the calcareous nannofossil biozones, which determine the nature of the Eocene/Oligocene boundary in the area. Our interpretation of the paleogeographic evolution of Neo-Tethys in the region increases the understanding of this significant stratigraphic event and the nature of the Paleogene tectono-sedimentary processes on the northern Arabian Plate.

## MATERIAL AND METHODS

The section at Qa' Faydat ad Dahikiya (31º34'34"N, 37º07'09"E; Figure 1) was logged in detail and a total of 49 samples were collected for microfossil studies at 20–50 cm intervals (Figure 2).

For the foraminiferal analyses, about 200 grams of dry rock sample were soaked in hydrogen peroxide, disaggregated in water, washed through a 63 µm sieve, and then dried. The number of species was calculated through semi-quantitative analysis from several fields of view at low magnification, using relative values as follows: abundant, > 26%; common, 16–25%; few, 6–15%; rare, 2–5%; very rare, < 2%. Nannofossils were identified by preparing smear-slides using the technique of Bramlette and Sullivan (1961), and subsequently analyzed with a polarizing microscope at 1,250 x magnification. Six calcareous nannofossil abundance levels have been chosen to represent the relative frequency of the taxa, and they are recorded as follows: A = abundant (1–10 specimens per field of view); C = common (1 specimen per 2–10 fields of view); F = few (1 specimen per 11–20 fields of view); R = rare (1 specimen per 21–100 fields of view); VR = very rare (one specimen per more than 100 field of view); and B = barren. Two classes of preservation are defined: G = good preservation; and M = moderate preservation.

## GEOLOGICAL SETTING

During the Paleogene, Jordan was part of a shallow epicontinental sea, which covered most of central and northeast Jordan (Alsharhan and Nairn, 1995; Powell and Moh'd, 2011). Deposition took place on a shallow-water carbonate platform that extended over present-day northern and eastern Arabia. The area under investigation, in the southern Al-Umari area, is dominated by Paleogene to Quaternary successions (Figure 1). The oldest exposed rock units in the study area are the Middle Eocene–Lower

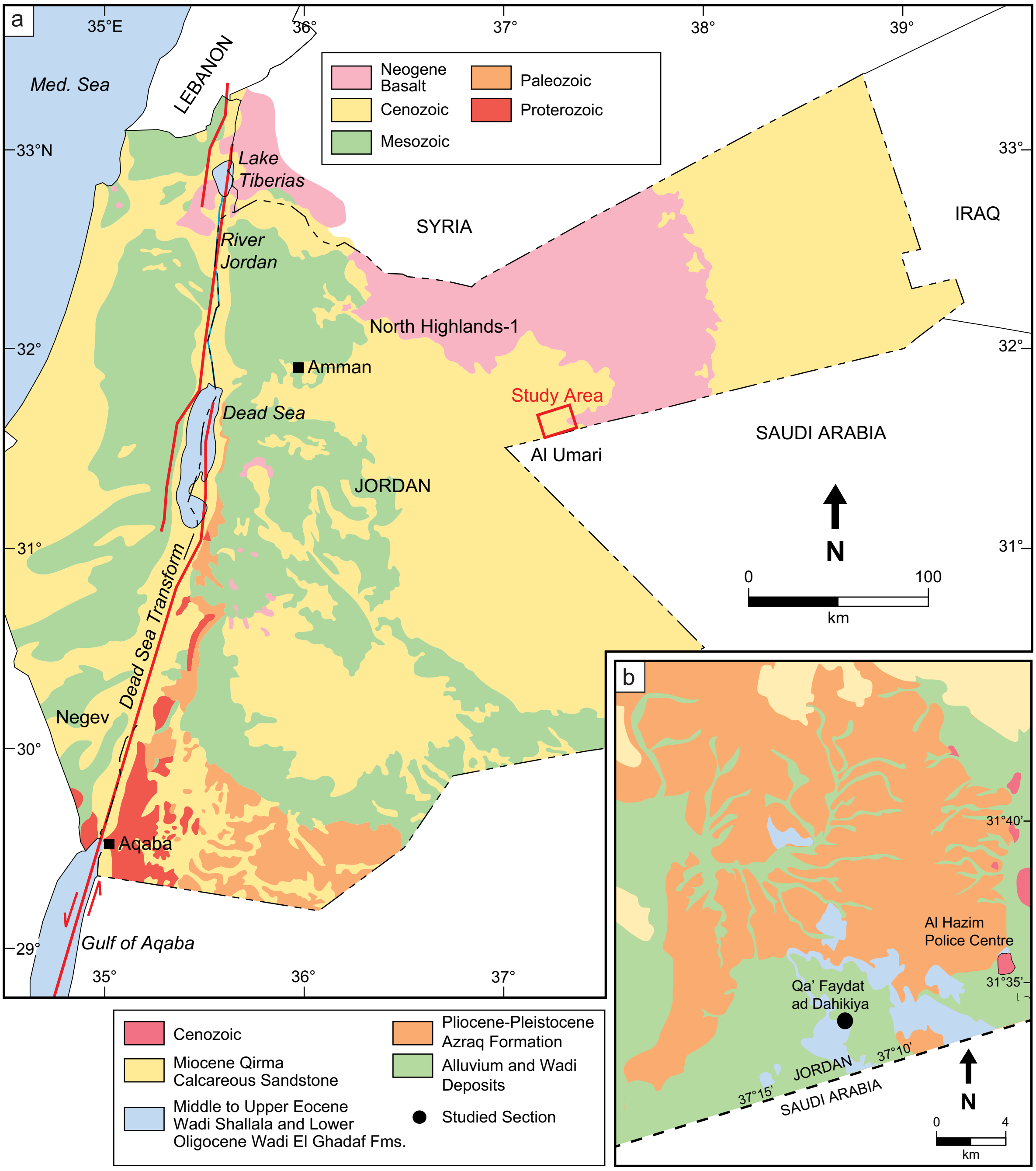


**Figure 1: (a) Generalized geological map of the region (after Natural Resource Authority, Jordan). (b) Location and geological map of the Qa' Faydat ad Dahikiya in the Eastern Desert of Jordan (modified from Rabba', 1997).**

Oligocene successions that form predominantly step-like, steep cliffs of white-grey to yellow, thick- and thin-bedded calcareous sediments (mostly chalky limestone), directly overlain by Miocene Qirma Calcareous Sandstone Formation (Figure 1). The latter is recorded only in the northwest of Qa' Faydat ad Dahikiya area. Volcanic rocks of Neogene–Quaternary age cover broad areas in the northern and eastern parts.

In the study area, the Azraq Formation (Pliocene–Pleistocene) unconformably overlies the older Paleogene rocks. Many normal faults with principal orientations northwest-southeast are located within the Wadi Sirhan rift zone, bounded by the NW–SE trending Fuluq and Sirhan faults (Rabba',

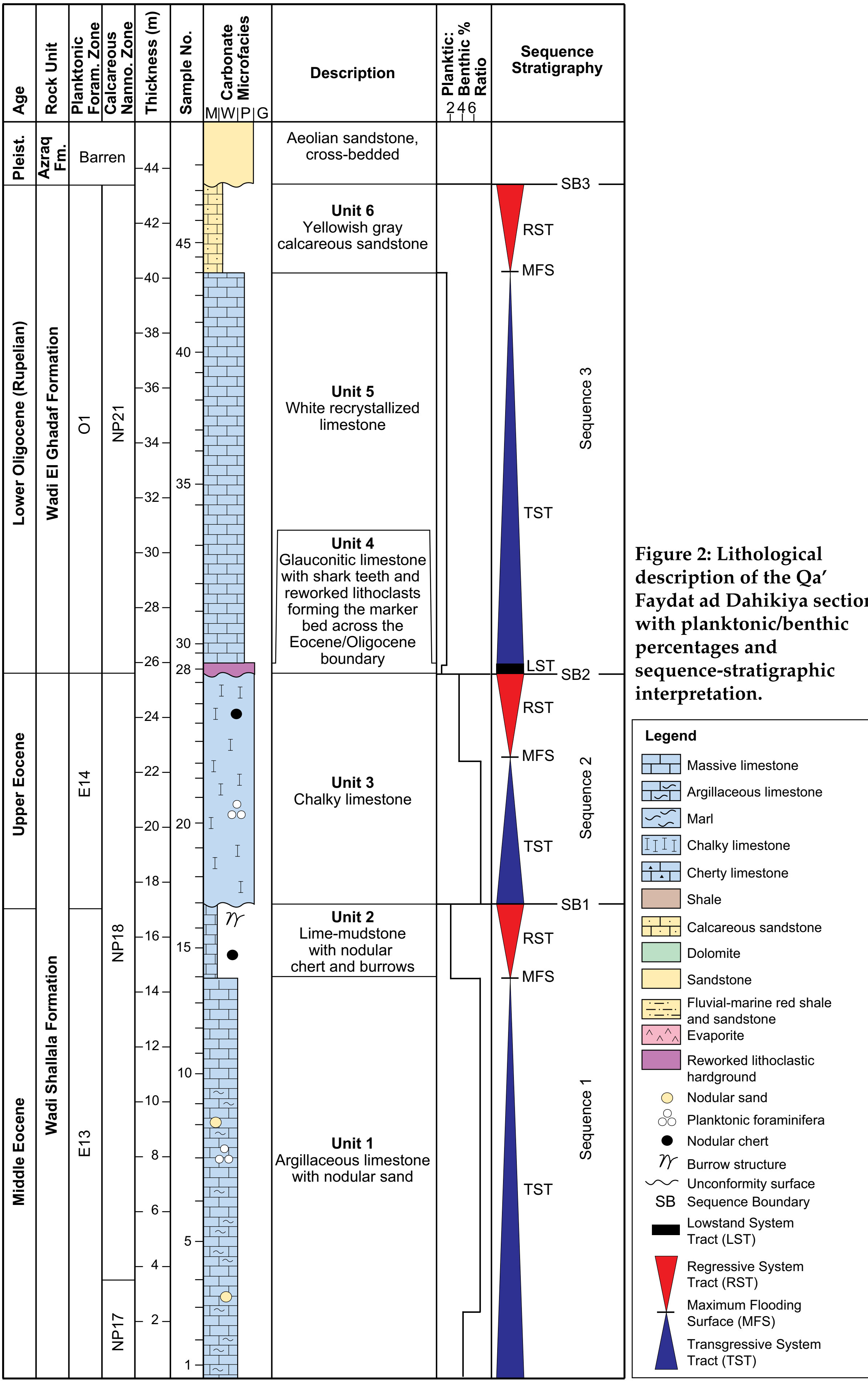


**Figure 2: Lithological description of the Qa' Faydat ad Dahikiya section, with planktonic/benthic percentages and sequence-stratigraphic interpretation.**

1997; Turner and Makhlouf, 2005). The most distinctive structure in the area is the Dahikiya Basin, which occurs as a subregional, SW-trending symmetrical anticline extending about 5 km, with dips of about 7º towards the southeast and 5º towards the northwest. Deformation of the Dahikiya Anticline is Miocene–Pliocene in age, probably related to intraplate deformation during development of the Syrian Arc that was, in turn, related to the opening of the Red Sea and left-lateral deformation along the Dead Sea Transform (Figure 1).

## LITHOSTRATIGRAPHY AND SEDIMENTATION

At Qa' Faydat ad Dahikiya the Paleogene succession spans the Middle Eocene–Lower Oligocene, and comprises the Middle–Upper Eocene Wadi Shallala Formation (Units 1 to 3) and Lower Oligocene Wadi El Ghadaf Formation (Units 4 to 6) formalized by Farouk et al. (2013) in eastern Jordan (Figures 2 and 3a). The two formations have distinctive lithologies and the boundary is taken below a distinctive mineralized hardground at the base of the Wadi El Ghadaf Formation (Figures 2 and 3b). The Wadi El Ghadaf Formation is equivalent to the Dhahkiye Chalk Formation of Late Eocene–Oligocene age (?) reported by Wetzel and Morton (1959) and Daniel (1963). The succession is correlated here with both the Dammam and the Asmari formations (Sharland et al., 2001; Farouk et al., 2013) which have long been established in Arabian Gulf stratigraphy (see Figure 5).

### Wadi Shallala Formation

The Wadi Shallala Formation (Middle to Upper Eocene) has a thickness of about 45 m and can be divided into the following three lithologic units, from base to top (Figures 2 and 3a):

**Unit 1** is ca. 14 m thick and composed largely of carbonate mudstone and wackestone characterized by variable recovery of planktonic foraminifera and sparse authigenic sand nodules interpreted as back-filled crustacean burrows (Figure 4a). It is generally fossiliferous with planktonic and benthonic foraminifera (the latter including *Bulimina jacksonensis*, *Uvigerina rippensis*, *U. jacksonensis*, *Marginulinopsis tuberculate* and *Cibicides* sp.). The planktonic foraminiferal species richness, reduced benthic species and absence of shallow-water indicators, indicates the foraminiferal lime-mudstone/wackestone was deposited in a quiet-water, deep middle- to outer-shelf setting below storm wave-base with open marine circulation.

**Unit 2** is ca. 2 m thick and is composed of chalky limestone, succeeded by burrow-fill and nodular chert in the form of spherical to subspherical nodules of variable sizes (< 5–20 cm diameter). They are either irregularly disseminated or coalescent within the upper part of the unit. The main lithology comprises lime mud, partially recrystallized, with minor quantities of dense micritized and badly preserved foraminiferal tests (Figure 4b). The fine-grained nature of this lithofacies and sparcity of its faunal content indicates deposition in a protected lower intertidal setting. Unit 2 represents a shallowing upward carbonate cycle moving from middle-shelf to shallow inner-shelf as documented by an upward decrease in the diversity of planktonic foraminifera and an increased diversity of benthic foraminifera (Figure 4b).

**Unit 3** is ca. 9 m thick and consists of hemipelagic chalky facies of foraminiferal wackestone lithofacies (Figures 2 and 4c). Unit 3 represents a new transgressive system tract, the base of which coincides with the Middle/Upper Eocene boundary. The frequent occurrence of planktonics (> 85%) with their high species diversity and deeper-marine benthic foraminifera, such as the genus *Uvigerinoides*, suggests that deposition occurred in a quiet-water, outer-shelf regime under conditions of normal salinity, well-oxygenated seawater and with open circulation. The P/B ratio decreases in the upper part of Unit 3 reflecting deposition in a shallow middle-shelf setting (Figure 2).

### Wadi El Ghadaf Formation

The Wadi El Ghadaf Formation (Early Oligocene) has a thickness of about 17 m and can be divided into the following three lithologic units (Figures 2 and 3a):

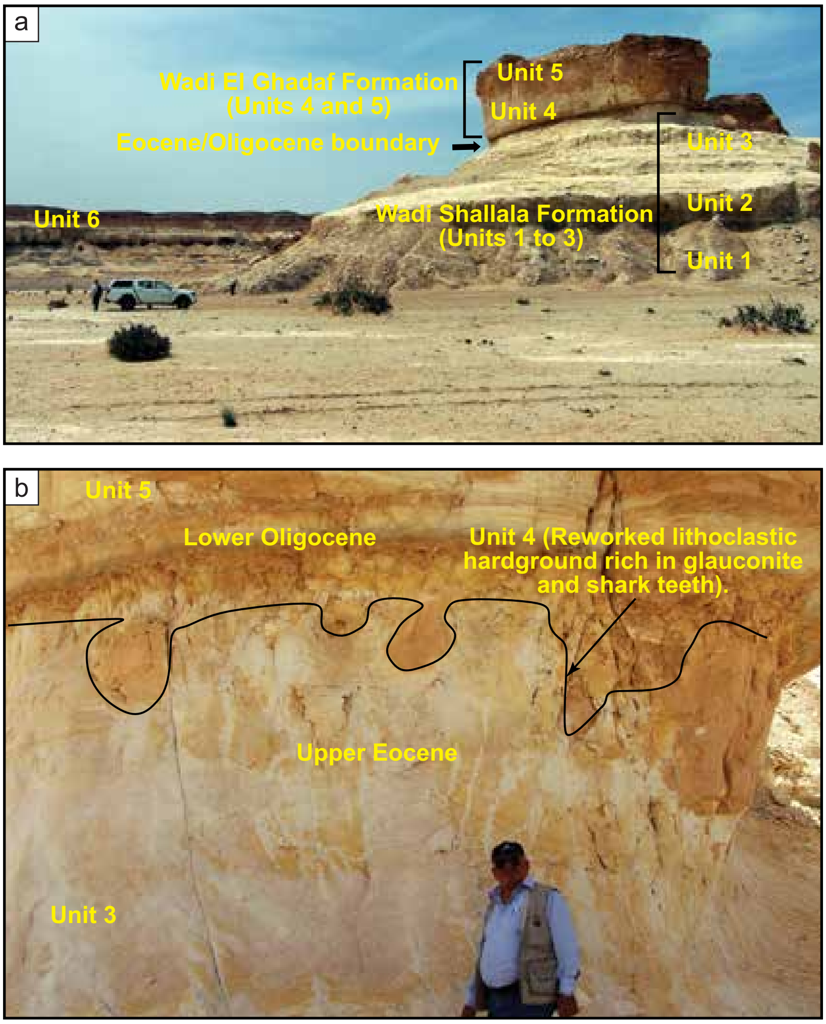


**Figure 3: (a) General view of the Qa' Faydat ad Dahikiya area showing the position of the Eocene/Oligocene boundary. (b) Close-up of the Eocene/Oligocene boundary in the Qa' Faydat ad Dahikiya area. Photos by S. Farouk.**

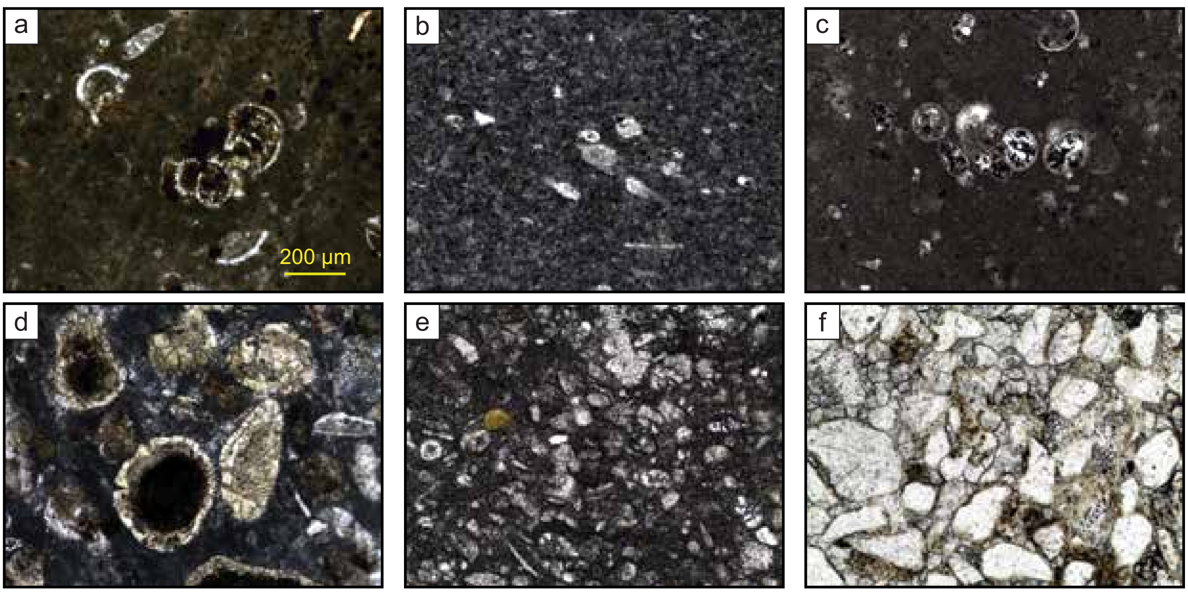


**Figure 4: Photomicrographs of microfacies types from the six units. (a) Unit 1: planktonic foraminiferal lime-mudstone. (b) Unit 2: benthic foraminiferal lime-mudstone. (c) Unit 3: planktonic foraminiferal lime-mudstone/ wackestone. (d) Unit 4: glauconitic phosphatic wackestone. (e) Unit 5: glauconitic recrystallized lime-mudstone. (f) Unit 6: poorly sorted quartz arenite. Scale bar is the same for all photos.**

**Unit 4** forms a marker bed of about 0.8 m thick just above the Eocene/Oligocene sequence boundary. (SB2) separates the Wadi Shallala and Wadi El Ghadaf formations. This boundary is a major unconformity (disconformity) easily recognizable in the field by the sharp contact of the reworked lithoclasts representing the hardground of lowermost Wadi El Ghadaf Formation (Figure 3b). The uppermost Eocene succession is missing in the study area as in most cases in Arabian and African plate settings (Figure 5) possibly reflecting major structural uplift and a submarine depositional hiatus resulting in a large time gap represented by the mineralized hardground (see Discussion). It consists of reworked lithoclasts of different size (Figures 2 and 4d), including glauconitic phosphatic wackestone containing marine reptile and fish bones, shark teeth, invertebrates and a few large foraminifera (nummulites). Discontinuity surfaces showing *in situ* crusts of iron and phosphate, as well as authigenic glauconite, indicate breaks in sedimentation and the establishment of firmgrounds and hardgrounds (Kennedy and Garrison, 1975; Jarvis, 1980; Powell and Moh'd, 2011). Sparse foraminifera are either heavily micritized or recrystallized with the foliated internal structure of nummulites preserved. Abul-Nasr and Thunell (1987) noted that the occurrence of phosphorite and occasional glauconite at this stratigraphic level in the region was a result of reworking during a phase of lowered sea level. We interpret this bed as a lowstand characterized by low rates of sedimentation, burrowing and reworking/mineralization of bottom sediments and is the culmination of a shallowing trend seen in the underlying regressive systems tract (Figure 2).

**Unit 5** This unit is ca. 14 m thick and consists of white, massive, cliff-forming limestone (Figure 3a). Foraminifera present are completely recrystallized into coarse pseudospar with chambers filled with granular sparry cement. Some of the glauconite grains, probably reworked from the underlying bed, show sharp boundaries with the cement (Figure 4e).

**Unit 6** is composed of yellowish-grey and brown bioturbated calcareous sandstone and may be equivalent to the Dahikiye Sandstone Member (Turner and Makhlouf, 2005), which is considered as the upper unit of the Wadi El Ghadaf Formation. Several thin cycles of weakly consolidated, poorly sorted, sparsely fossiliferous and thin-laminated quartz arenite and fossiliferous calcareous sandstone are present (Rabba', 1997). The upper sandstone bed is silty, massive, argillaceous and bioturbated with both vertical and inclined burrows. It consists of very fine- to coarse-grained, rounded to

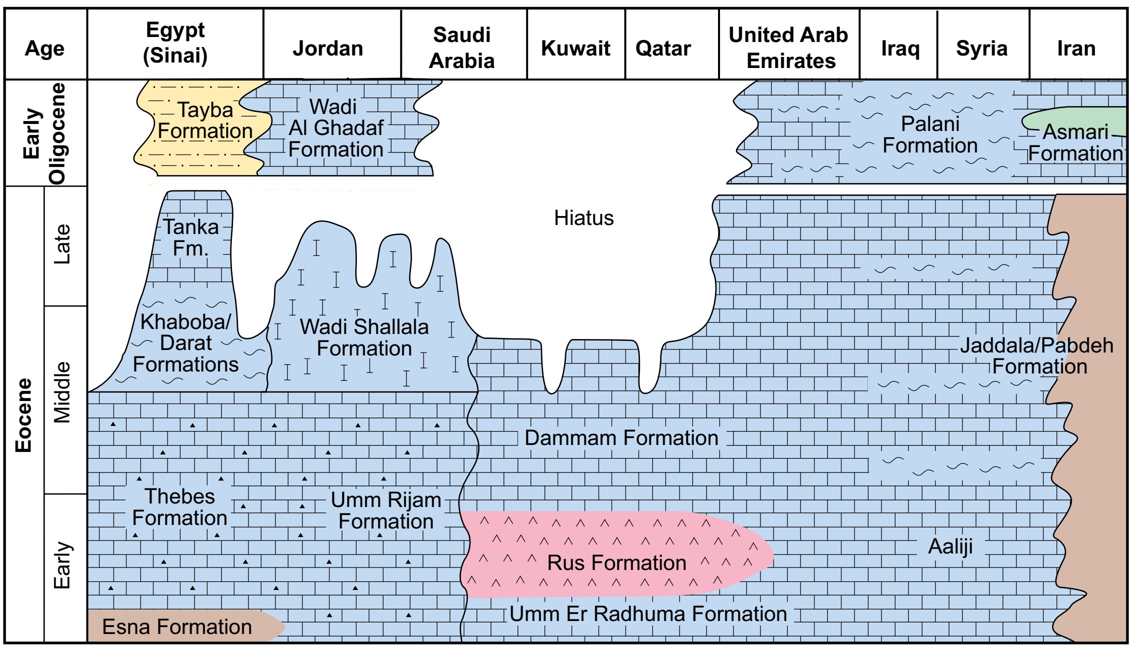


**Figure 5: Comparison of lithostratigraphic schemes for the Paleogene succession across the African/Arabian plates showing lateral variations in lithofacies and the widely distributed unconformity of variable duration across the Eocene/Oligocene boundary (modified after Sharland et al., 2001; Farouk et al., 2013). For symbol key see Figure 2.**

subangular quartz with silt as a minor component (Figure 4f). The sparse fauna and thin-lamination indicate that the sandstone was deposited in a beach to lower shoreface setting receiving significant detrital influx from the hinterland. This member is nearly barren of foraminifera and denotes a major fall in eustatic sea level that characterized the regressive phase at the end of the Early Oligocene on the northern Arabian Plate (Figure 2).

## CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY

The samples generally contain rare to abundant coccoliths, and the preservation is, in general, moderate to good. The distribution of the identified nannofossil taxa are shown in Figure 6 and classified according to calcareous nannofossil zonal scheme of Martini (1970, 1971). Representative nannofossil taxa are presented on Plates 1–3. Abbreviations used in the present study are: LO = lowest occurrence, LCO = lowest common occurrence and HO = highest occurrence. Two Middle Eocene and one Lower Oligocene nannofossil zones have been recognized from the studied section.

### *Discoaster saipanensis (NP17) Zone*

**Definition:** This zone was originally defined by Martini (1971) as the interval from the highest occurrence (HO) of *Chiasmolithus solitus,* at the base, to the lowest occurrence (LO) of *Chiasmolithus oamaruensis,* at the top. In the present study, we used the lowest common occurrence (LCO) of *C. oamaruensis* to define the top of this zone.

**Thickness:** 3.7 m, equivalent to the lower beds in the exposed part of the Wadi Shallala Formation.

**Assemblage:** This interval includes the following characteristic taxa (Figure 6): *Reticulofenestra hillae*, *Chiasmolithus grandis*, *Sphenolithus moriformis*, *Reticulofenestra umbilica*, *Cribrocentrum reticulatum*, *C. isabellae*, *Dictycoccites bisectus*, *D. tanii*, *D. saipenensis* and *D. barbadiensis*. In addition, rare occurrences of *Isthmolithus recurvus* (side views) are present.

**Remarks:** The highest occurrence (HO) of *Chiasmolithus solitus* defines the NP16/NP17 zonal boundary in the tropical areas (Martini, 1970) or CP14a/CP14b of Okada and Bukry (1980). In the higher latitudes sites such as Jordan, the highest occurrence (HO) of *C. solitus* occurs at the base of Zone NP18 and coincides with the biohorizon of the lowest common occurrence (LCO) of *C. oamaruensis* (Persico and Villa, 2008). On the other hand, the recognition of the top of Zone NP17 has been difficult at Alano (northeast Italy) because *Chiasmolithus oamaruensis* is exceedingly rare and exhibits a discontinuous abundance pattern, especially in the lower part of its range (Agnini et al., 2011). In the studied section, the absence of *C. solitus* in sample D/1 may indicate that the base of the current succession can be attributed to NP17 (*D. saipanensis* Zone).

### *Chiasmolithus oamaruensis (NP18) Zone*

**Definition:** This zone was originally defined by Martini (1971) as the interval from the lowest occurrence of *Chiasmolithus oamaruensis* to the lowest occurrence of *Isthmolithus recurvus*. In the present study, the top of this zone occurs at the Eocene/Oligocene unconformity.

**Thickness:** The upper 24 m of the Wadi Shallala Formation.

**Assemblages:** In addition to the marker taxon (*C. oamaruensis*), many taxa are recorded in this zone: *Helicosphaera bramelettei, Cyclicargolithus floridanus, Helicosphaera compacta, Neococcolithes dubius, Lanternithus minutus*; in addition there are rare occurrences of *Chiasmolithus grandis* in the basal part of this zone (Figure 6).

**Remarks:** The LO of *C. oamaruensis* defines the base of Zone NP18, and is used as a secondary criterion for defining the CP15 Zone (Okada and Bukry, 1980). This species is always a rare component among nannofossil assemblages in low and middle latitude areas, where its LO is difficult to recognize (Wei and Wise, 1989). The appearance of C. *oamaruensis* usually precedes the first occurrence of *Isthmolithus recurvus* (Martini, 1970, 1971). Persico and Villa (2008) distinguish the lowest occurrence

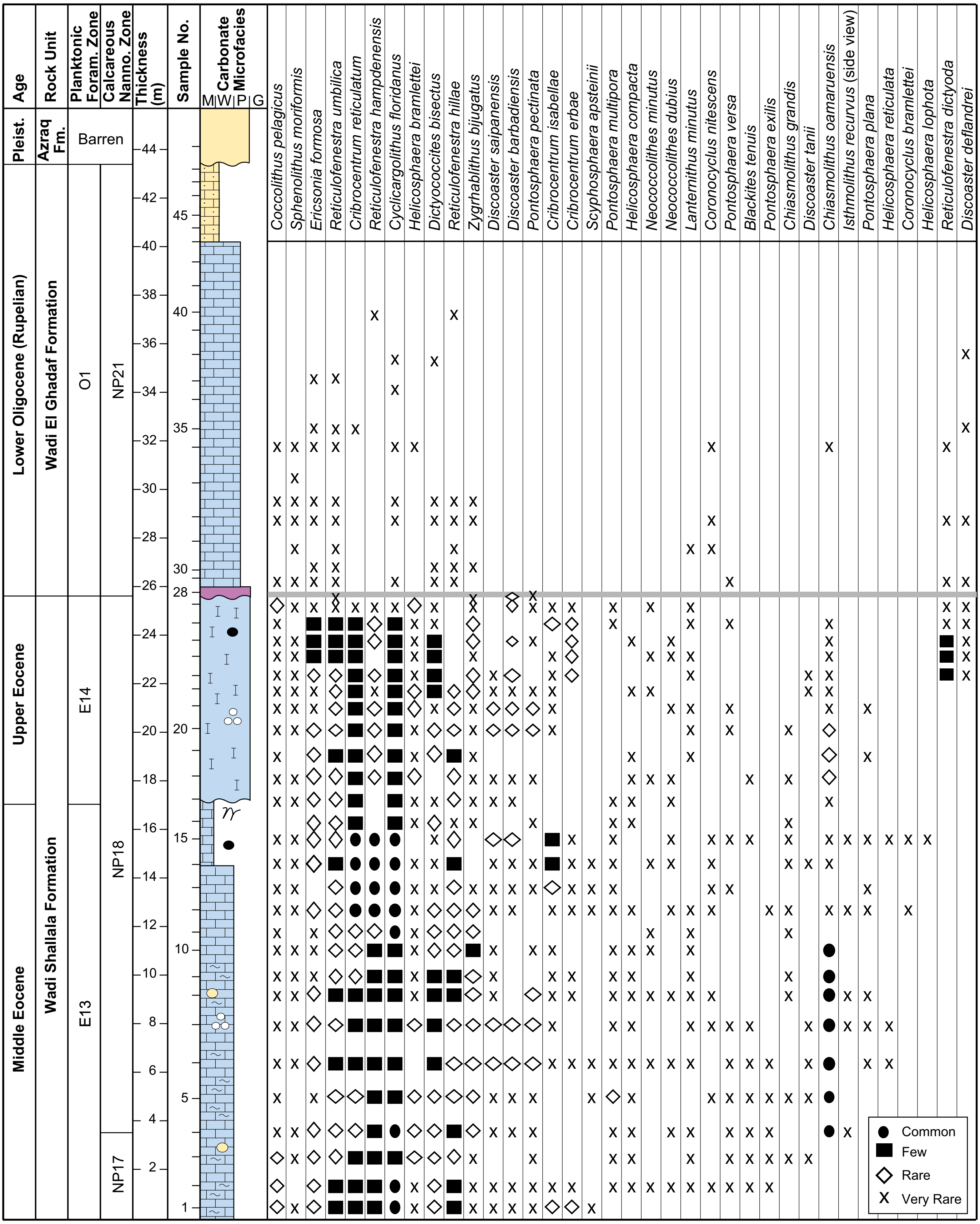


**Figure 6: Stratigraphic distribution of the identified calcareous nannofossils, and biostratigraphic zones in the Qa' Faydat ad Dahikiya section. For symbol key see Figure 2.**

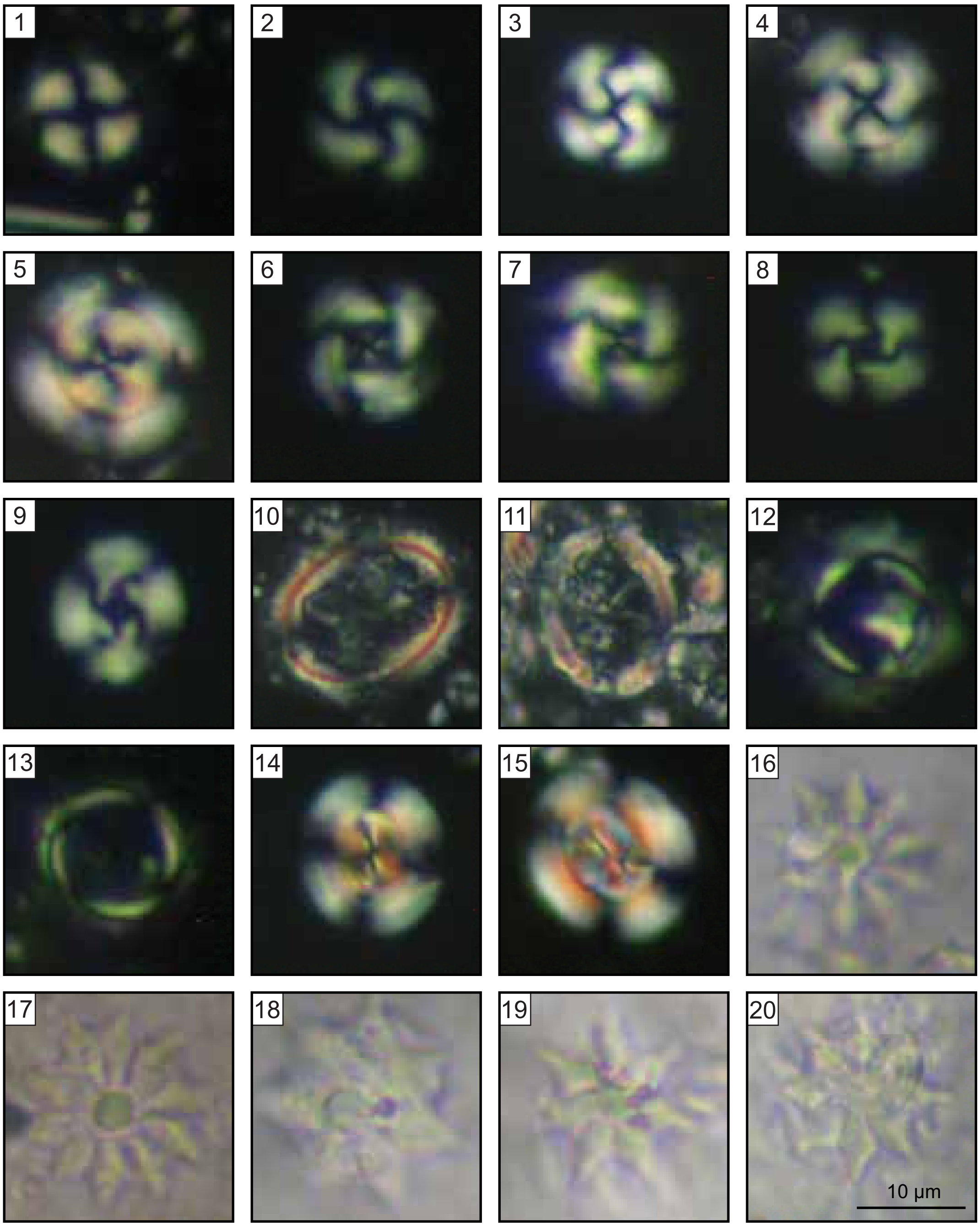


**Plate 1: Photomicrographs in cross-polarized (figures 1–15) and plane-polarized (figures 16–20) light of calcareous nannofossils from the Middle Eocene to Upper Eocene Wadi Shallala Formation collected from the Qa' Faydat ad Dahikiya area in the Eastern Desert of Jordan. The scale applies to all figures.**

**1:** *Ericsonia formosa* **(Kamptner, 1963); sample 7.**

**2-4:** *Cribrocentrum erbae* **Fornaciari et al., 2010; 2, sample 15; 3, sample 6; 4, sample 12.**

**5:** *Cribrocentrum isabellae* **Fornaciari et al., 2010; sample 14.**

**6–7:** *Cribrocentrum reticulatum* **(Gartner and Smith, 1967); 6, sample 2; 7, sample 12.**

**8:** *Reticulofenestra dictyoda* **(Deflandre *in* Deflandre and Fert, 1954); sample 27.**

**9:** *Cyclicargolithus floridanus (***Roth and Hay in Hay et al. 1967***)***; sample 16.**

**10–11:** *Chiasmolithus grandis* **(Bramlette and Riedel, 1954), sample 3.**

**12–13:** *Coronocyclus nitescens* **(Kamptner, 1963); 12, sample 21; 13, sample 9.**

**14–15:** *Dictyococcites bisectus* **Hay, 1966; 14, sample 10; 15, sample 26.**

**16–17:** *Discoaster barbadiensis* **Tan, 1927; 16, sample 6; 17, sample 25.**

**18–20:** *Discoaster saipanensis* **Bramlette and Riedel, 1954; 18, sample 21; 19, sample 18; 19, sample 20.**

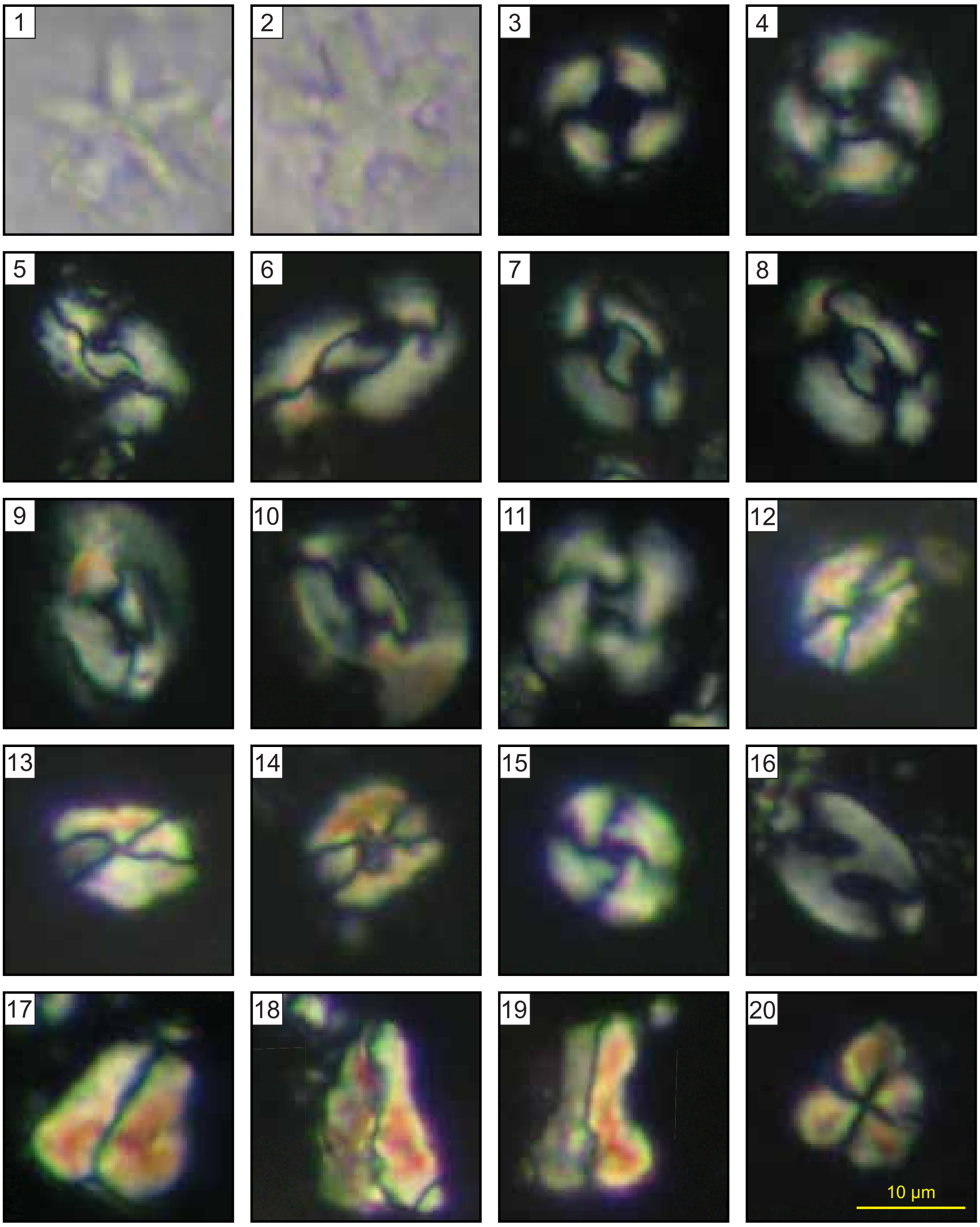


**Plate 2: Photomicrographs in plane-polarized (figures 1–2) and cross-polarized (figures 3–20) light of calcareous nannofossils from the Middle Eocene to Upper Eocene Wadi Shallala Formation from the Lower Oligocene Wadi El Ghadaf Formation collected from the Qa' Faydat ad Dahikiya area in the Eastern Desert of Jordan. The scale applies to all figures.**

**1–2:** *Discoaster tanii* **Bramlette and Riedel, 1954; 1, sample 22; 2, sample 5.**

**3–4:** *Ericsonia formosa* **(Kamptner, 1963); 3, sample 13; 4, sample 17.**

**5–8:** *Helicosphaera bramlettei* **Muller, 1970; 5, sample 4; 6, sample 13; 7, sample 21; 8, sample 16.**

**9–10:** *Helicosphaera compacta* **Bramlette and Wilcoxon, 1967; 9, sample 18; 10, sample 12.**

**11:** *Reticulofenestra hampdenensis* **Edwards (1973); sample 14.**

**12–14:** *Lanternithus minutus* **Stradner, 1962; 12, sample 11; 13, sample 8; 14, sample 27.**

**15:** *Cyclicargolithus floridanus* **(Roth, Hay, in Hay et al., 1967) Bukry (1971); sample 26.**

**16:** *Pontosphaera exilis* **(Bramlette and Sullivan, 1961) Perch-Nielsen (1971); sample 4.**

**17–19:** *Zygrhablithus bijugatus* **(Deflandre *in* Deflandre and Fert, 1954); 17, sample 20; 18, sample 16; 19, sample 25.**

**20:** *Sphenolithus moriformis* **(Bronnimann and Stradner, 1960); sample 30.**

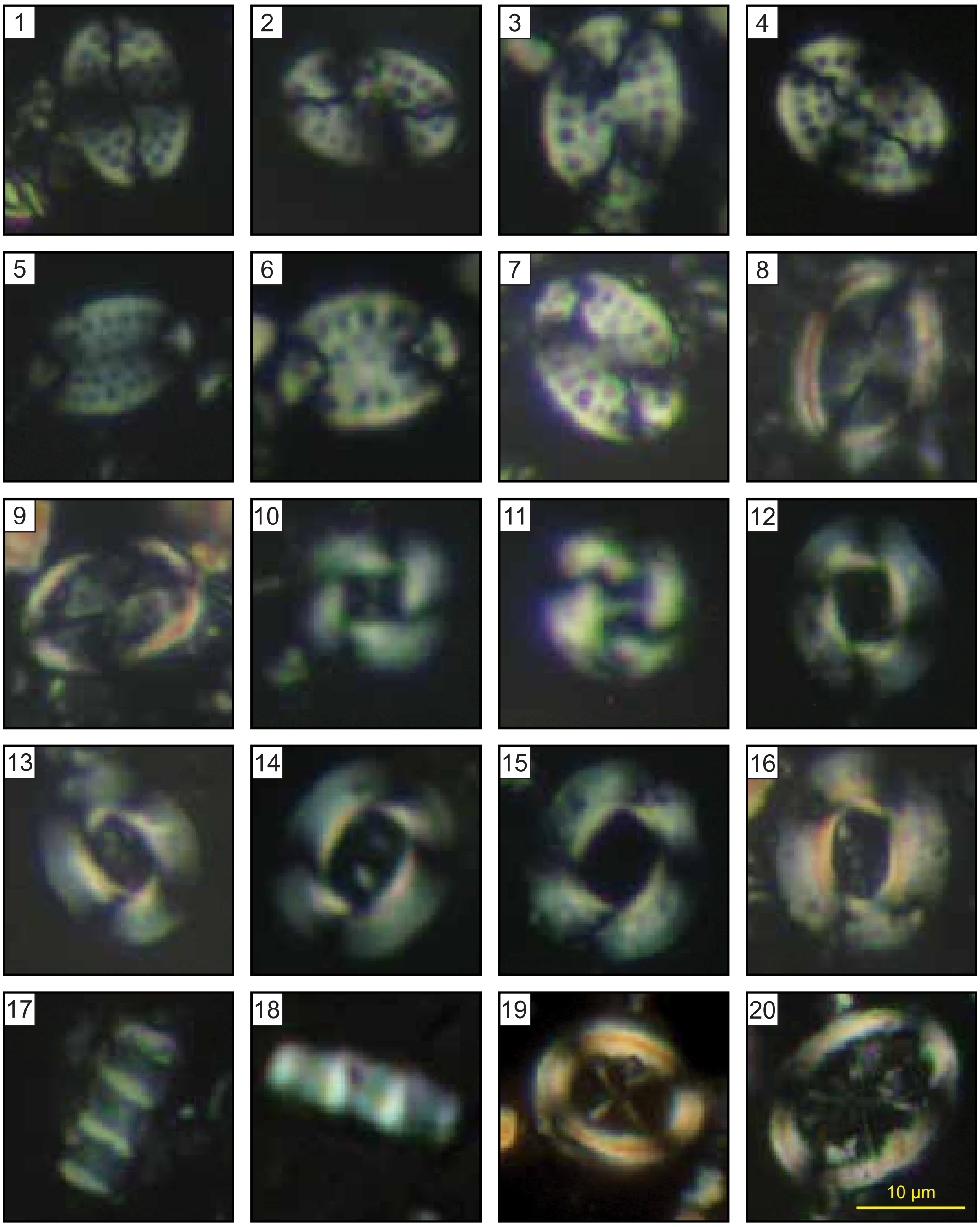


**Plate 3: Photomicrographs in cross-polarized light of calcareous nannofossils from the Middle Eocene to Upper Eocene Wadi Shallala Formation and the Lower Oligocene Wadi El Ghadaf Formation collected from the Qa' Faydat ad Dahikiya area in the Eastern Desert of Jordan. The scale applies to all figures.**

**1–7:** *Pontosphaera multipora* **(Kamptner, 1948); 1–2, sample 8; 3–5, sample 14; 6, sample 26; 7, sample 16.**

**8–9:** *Pontosphaera versa* **(Bramlette and Sullivan, 1961); 8, sample 26; 9, sample 7.**

**10:** *Cribrocentrum reticulatum* **(Gartner and Smith, 1967); sample 2.**

**11:** *Reticulofenestra hampdenensis* **Edwards, 1973, sample 13.**

**12–13:** *Reticulofenestra hillae* **Bukry and Percival, 1971; 12, sample 9; 13, sample 1.**

**14–16:** *Reticulofenestra umbilica* **(Levin, 1965); 14, sample 8; 15, sample 6; 16, sample 22.**

**17–18:** *Isthmolithus recurvus* **Deflandre, 1954; Side views, sample 4.**

**19–20:** *Chiasmolithus oamaruensis* **(Deflandre, 1954); 19, sample 17; 20, sample 32.**

of *C. oamaruensis* in the upper Zone NP16. They identified NP18 (*C. oamaruensis* Zone) to include the interval from the lowest common occurrence (LCO) of *C. oamaruensis* to the LCO of *Isthmolithus recurvus*.

The HO of *C. grandis* defines the base of Zone CP15a (Okada and Bukry, 1980). The species is common at low to middle latitudes, whereas it is found to be exceedingly rare or absent at the high latitudes (Wei and Wise, 1990a, b, 1992; Wei and Thierstein, 1991). The relative position of the HO of *C. grandis* and LO of *C. oamaruensis*, the two alternative events used for recognizing the base of the Zone CP 15a, are highly contradictory. Most nannofossil specialists report the HO of *C. grandis* just below the LO of *C. oamaruensis* (Wei and Wise, 1989; Berggren et al., 1995; Marino and Flores, 2002a, b). At the Wadi Hitan sections in Egypt, *Chiasmolithus grandis* overlaps the lower range of *C. oamaruensis* (Strougo et al., 2013), which is in agreement with observations recorded in the present study. The HO of *C. grandis* is thus a problematic biohorizon (Agnini et al., 2014). The discontinuous and sporadic occurrences of *C. oamaruensis*, and demonstrated diachronity of its first appearance over latitudinal distance (Wei and Wise, 1992; Marino and Flores, 2002a, b; Villa et al., 2008; Fornaciari et al., 2010), however, indicate that this biohorizon is a poor guiding criterion for definition of a stage boundary.

Two new species of *Cribrocentrum*, *C. erbae* and *C. isabellae* have been identified by Fornaciari et al. (2010). These two species were firstly recorded in Zone NP17 (Middle Eocene) in the present study. The LO of *C. isabellae* coincides with LCO of *I. recurvus* in northern Italy and can be used as secondary bioevents for the Middle/Upper Eocene boundary interval as suggested by Fornaciari et al. (2010). At Wadi Hitan in Egypt, *C. isabellae* first appears in the top part of Zone P14 (Middle Eocene), and it seems to appear in a lower horizon than in northern Italy (Strougo et al., 2013). These two bioevents (LO of *C. isabellae* and LCO of *I. recurvus*) cannot be used to delineate the Middle Eocene/Upper Eocene boundary interval in the Jordan sections, due to the difficulty in defining the Zone NP19-20.

The LO of *Isthmolithus recurvus* defines the NP18/NP19 zonal boundary in standard scheme of Martini (1971), its lowest common occurrence (LCO) characterizing the base of Zone NP19-20 (Persico and Villa, 2008). The LO of *I. recurvus* is almost very rare and has a sporadic distribution and first appearance together with the LO of *Chiasmolithus oamaruensis* and has been found associated with the Middle Eocene planktonic foraminiferal assemblage. Therefore it cannot be used either as evidence for the Upper Eocene or as indicating the base of Zone NP19-20. Strougo et al. (2013) demonstrated that the ranges of late Middle Eocene and Late Eocene calcareous nannofossil index taxa do not correlate well with established zonal schemes in many sections worldwide. The LO of *I. recurvus* is in fact much older than generally assumed in the literature (Strougo and Faris, 2008), in agreement with other reports from outside of Egypt as well (Villa et al., 2008; Fornaciari et al., 2010). In the Southern Ocean, the LO of *Isthmolithus recurvus* occurs near the top of the Middle Eocene Zone NP18 (Persico and Villa, 2008).

## *Ericsonia subdisticha (NP21) Zone*

**Definition:** This zone is defined by the HO of *Discoaster saipanensis* up to the HO of *Ericsonia formosa.*

**Thickness:** The upper 17 m of the investigated section, are assigned to zone NP21.

**Associated species:** The zone is characterized by low species diversity. *Reticulofenestra umbilica, R. hillae, R. dictyoda*, *Sphenolithus moriformis*, *Cyclicargolithus floridanus* and *Zygrhablithus bijugatus.* Other taxa such as *Cribrocentrum reticulatum, C. erbae, C. isabellae,* and *Discoaster tanii* have their last appearances in Zone NP18 of the study section. The only discoaster observed in the Lower Oligocene Zone NP21 is *Discoaster deflandrei*.

**Remarks:** The base of Zone NP21 is defined by the highest occurrence (HO) of *D. barbadiensis* and/ or *D. saipanensis*. The Eocene/Oligocene boundary, in terms of calcareous nannofossil events, is drawn at the top of NP20 Zone and is defined by the last appearance datum of the disk-shaped discoasters represented by *Discoaster saipanensis* (Perch-Nielsen, 1985). Major changes in nannofossil assemblages were observed near the Eocene/Oligocene boundary in the study section. In addition to the last appearances of *D. barbadiensis* and *D. saipanensis*, several species have last occurrences:

*C. erbae, C. reticulatum* and *C. isabellae*. A distinct decrease in diversity and abundance of calcareous nannofossil assemblages towards the Eocene/Oligocene boundary is also noted. Among 36 Upper Eocene nannofossil taxa, 17 species are recorded in the Lower Oligocene Zone (NP21).

## PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY

Planktonic foraminifera are marked by a high diversity and abundance with good preservation in the Eocene interval, while the Lower Oligocene sediments contain only few, poorly preserved species characterized commonly by recrystallization of small sized tests. Selected taxa are illustrated in Plate 4. We used the Eocene planktonic foraminifera scheme of Toumarkine and Luterbacher (1985) and Berggren and Pearson (2005) denoting "E" for Eocene zonations and "O" for Oligocene zonation. Three biostratigraphic intervals are recognized in Qa' Faydat ad Dahikiya area. From base to top, these are as follows:

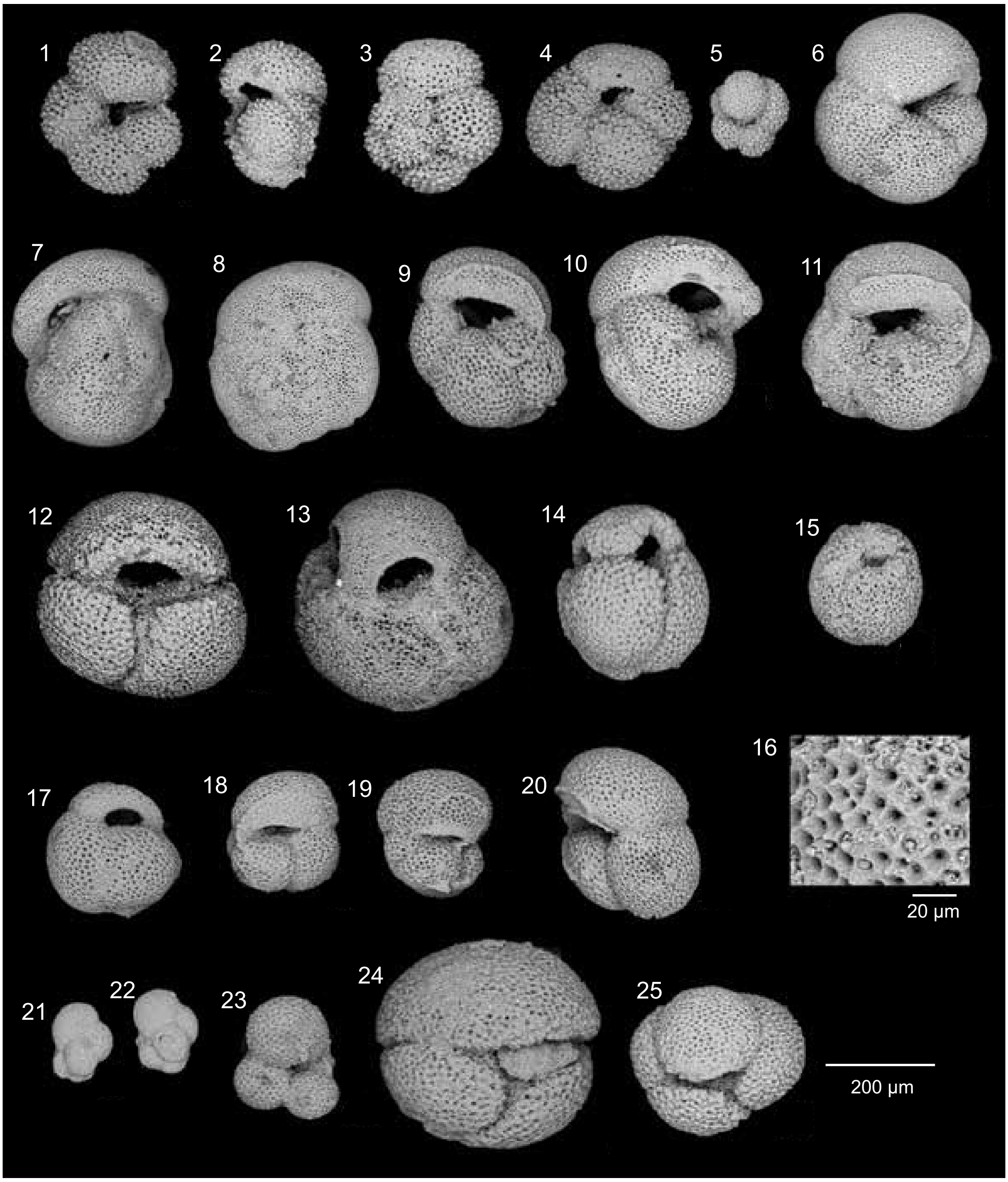


**Plate 4:** *See facing page for caption.*

## *Truncorotaloides rohri (E13) Zone*

**Definition:** Originally this zone was defined as an interval from the HO of *Orbulinoides beckmanni* to the HO of *Truncorotaloides rohri*. The base of this zone does not crop out in the studied section.

**Assemblages:** This interval is marked by a low diversity and high abundance of spinous forms of planktonic foraminifera (e.g. *Truncorotaloides* and *Acarinina* spp.) with the complete absence of *Morozovelloides*, while the non-umblicate forms belonging to the *Globigerinatheka* group are either absent or rare in the basal part, but increase upward. The most dominant taxa in this zone are *Acarinina bullbrooki*, *Turborotalia pomeroli*, *T. pseudoampliapertura*, and *Truncorotaloides rohri* (Figures 7 and 8). Both the abundance and diversity of planktonic foraminifera drop sharply near the top of this zone.

**Remarks:** Haggag (1989) reported that *Morozovelloides* becomes extinct slightly before the first appearance of *Truncorotaloides* spp. In the present study, absence of any *Morozovelloides* together with the presence of muricate species (e.g. *Acarinina bullbrooki* and *Truncorotaloides rohri*), which decrease in frequency upward, reflects the uppermost part of E13 Zone in the basal part of the section, up to 14.40 m level (samples 1–16). This interval can be correlated to the upper part of the *Morozovella crassata* (E13) in the zonal scheme of Berggren and Pearson (2005) and Wade et al. (2011, 2012). In the present study, we cannot use the HO of *Morozovella crassata* because the genus *Morozovella* is absent in the studied section. *Morozovella crassata* is required to distinguish E13 and E14 zones according to concept of Berggren and Pearson (2005). However, Mukhopadhyay (2005) reported the LO of *T. cerroazulensis* in the *Truncorotaloides rohri* P14 Zone of Middle Eocene in contrast to Toumarkine and Luterbacher (1985) who state that it appears early in the *Morozovella lehneri* Zone. In the present study the LO of *T. cerroazulensis* occurs in this zone.

## *Globigerinatheka semiinvoluta (E14) Zone*

**Definition:** This zone is defined by the HO of muricate species (large *Acarinina* and *Truncorotaloides* spp.) to the HO of *Globigerinatheka semiinvoluta*. In the current study, the top of this zone cannot be defined due to a major hiatus at the Eocene/Oligocene boundary (Figure 3b).

**Thickness:** This interval has a thickness of 9.5 m.

**Assemblages:** In this zone, *Dentoglobigerina tripartita*, *Turborotalia pseudoampliapertura*, *T. cerroazulensis* and *Globigerinatheka index* group become very frequent. Very rare specimens of *Hantkenina alabamensis* are recorded higher in sample 26.

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**Plate 4 (facing page): Planktonic foraminifera from the Middle Eocene to Upper Eocene Wadi Shallala Formation and the Lower Oligocene Wadi El Ghadaf Formation collected from the Qa' Faydat ad Dahikiya area in the Eastern Desert of Jordan. Scale of 200 µm applies to all figures except figure 16 (20 µm).**
**1–3:** *Truncorotaloides rohri* **Brönnimann and Bermudez, 1953; sample 14.**
**4:** *Acarinina bullbrooki* **(Bolli, 1957); sample 4.**
**5:** *Acarinina medizzai* **(Toumarkine and Bolli, 1975); sample 16.**
**6–8:** *Turborotalia cerroazulensis* **(Toumarkine and Bolli, 1970); sample 26.**
**9–10:** *Turborotalia pomeroli* **(Toumarkine and Bolli, 1970); sample 4.**
**11:** *Turborotalia pseudoampliapertura* **(Blow and Banner, 1962); sample 25.**
**12:** *Globigerinatheka index* **(Finlay, 1939); sample 15.**
**13:** *Globigerinatheka aegyptiaca* **(Haggag and Bolli, 1995); sample 23.**
**14:** *Globigerinatheka tropicalis* **(Blow and Banner, 1962); sample 18.**
**15–16:** *Globigerinatheka semiinvoluta* **(Keijzer, 1945); sample 23.**
**17:** *Globigerina praeturritilina* **Blow and Banner, 1962; sample 4.**
**18–19:** *Subbotina linaperta* **(Finlay, 1939); sample 9.**
**20:** *Globigerina tapuriensis* **Blow and Banner, 1962; sample 9.**
**21–22:** *Cassigerinella chipolensis* **(Cushman and Ponton, 1932); sample 30.**
**23:** *Subbotina eocaena* **(Guembel, 1868); sample 16.**
**24:** *Dentoglobigerina tripartita* **(Koch, 1926); sample 16.**
**25:** *Dentoglobigerina pseudovenezuelana* **(Blow and Banner, 1962); sample 23.**

**Remarks:** In the present study, an interval 4 m thick contains a planktonic assemblage differing slightly from the underlying E13 Zone. It is characterized by the extinction of the large spinose and muricate species slightly below the LO of *Globigerinatheka semiinvoluta*, as reported previously by many authors from most parts of Egypt (e.g. Haggag, 1990; Strougo, 1992, 2008; Haggag and Luterbacher, 1995; Strougo et al., 2013). Therefore, Haggag (1990) introduced a new Upper Eocene planktonic foraminiferal zone called *Turborotalia pseudoampliapertura* Zone. It is defined as the interval from the HO of *Truncorotaloides rohri* to the LO of *Globigerinatheka semiinvoluta.* Actually, a similar interval is recorded by other authors: in the western Negev by Benjamini (1980), from the Spanish Pyrenees by Canudo and Molina (1992), and from the Jabal Hafit of United Arab Emirates by Anan et al. (1992). The same interval is clearly seen around the Bartonian/Priabonian boundary in the Alano section (northeast Italy). At that locality Agnini et al. (2011) reported the HO of large muricate forms (large *Acarinina* and *Morozovella*) occurring ca. 11 m below the lowest occurrence of *G. semiinvoluta* (Figure 9).

Based on this observation at different localities, Strougo et al. (2013) classified Zone P15 at Wadi Hitan in Egypt, into a two-fold division as: a *T. pseudoampliapertura* Subzone (P15a) and a *G. semiinvoluta* Subzone (P15b). However, in other Tethyan sections, the LO of *Globigerinatheka semiinvoluta* has been reported in the Middle Eocene slightly before the HO of spinose and muricate species (e.g. Berggren and Miller, 1988; Berggren et al., 1995; Mancin et al., 2003; Luterbacher et al., 2004; Wade, 2004; Premoli Silva et al., 2006). Subzones P15a and P15b are approximately equivalent to Zone *Turborotalia cerroazulensis* of Toumarkine and Bolli (1970) and Mukhopadhyay (2005). Absences of higher lineage *Turborotalia* (e.g. *T. cocoaensis, T. cunialensis*) may denote the absence of the uppermost parts of the Upper Eocene *Globigerinatheka semiinvoluta* (P15b) Subzone. Correlation of the LO of *Globigerinatheka semiinvoluta* between different provinces is thus not reliable as a global marker for the Middle/Upper Eocene boundary (Figure 9).

In the present study, we prefer to use the HO of large muricate species to place the Middle/Upper Eocene boundary. According to many authors based on different localities from tropical and Mediterranean regions (e.g. Toumarkine and Luterbacher, 1985; Mancin et al., 2003; Agnini et al., 2011; Strougo et al., 2013), the HO of muricate species can be considered as an excellent reliable bioevent across the Middle/Upper Eocene. This group of planktonic foraminifera is clearly recognizable and widely distributed in different provinces. In the present study, we consider the *Turborotalia pseudoampliapertura* (P15a) Subzone as equivalent to lower part of *Globigerinatheka semiinvoluta* Zone. In the western North Atlantic (Ocean Drilling Program Site 1052), the large acarininids (*Acarinina praetopilensis*) terminate 10 kyr prior to the extinction of *M. spinulosa* and, furthermore, small acarininids (*Acarinina medizzai* and *Acarinina echinata*) continue into the Late Eocene (Wade, 2004). In the present study, we report very few specimens of *Acarinina medizzai* present only in the lower part of this zone (Figure 9).

### *Cassigerinella chipolensis/Pseudohastigerina micra (O1) Zone*

**Definition:** This zone is defined by the overlap of *Pseudohastigerina micra* and *Cassigerinella chipolensis*.

**Thickness:** The upper 16 m of the investigated section, above the 28 m level, are assigned to Zone O1 of Berggren and Pearson (2005).

**Assemblage:** Planktonic foraminifera are frequent, but preservation is poor due to infilling and recrystallization. Characteristic taxa include *Cassigerinella chipolensis*, *Paragloborotalia nana*, *Globigerina praebulloides*, *Pseudohastigerina naguewichiensis*, *Catapsydrax unicavus* (Figure 7).

**Remarks:** Sharp vertical faunal changes above the unconformity surface across the Eocene/Oligocene contact is observed. A marked change in the size, preservation and diversity of the foraminiferal fauna from Middle Eocene to Lower Oligocene are noted. Faunas from this zone are small in size and low in diversity, and are present only in the fine fraction of the washed residue. The absence of any Eocene marker species (e.g. *Turborotalia cerroazulensis* lineage) with first appearance of typical Oligocene species *Cassigerinella chipolensis*, in addition to the recognition of nannofossil Zone NP21 confirms the presence of the O1 Zone, which characterizes the Early Rupelian Stage. This zone approximates to the *Turborotalia cerroazulensis/Pseudohastigerina* spp. Zone (P18) which has been described previously in northwestern and eastern Jordan by Farouk et al. (2013), and is also equivalent to the *Pseudohastigerina naguewichiensis* Zone of Berggren and Pearson (2005).

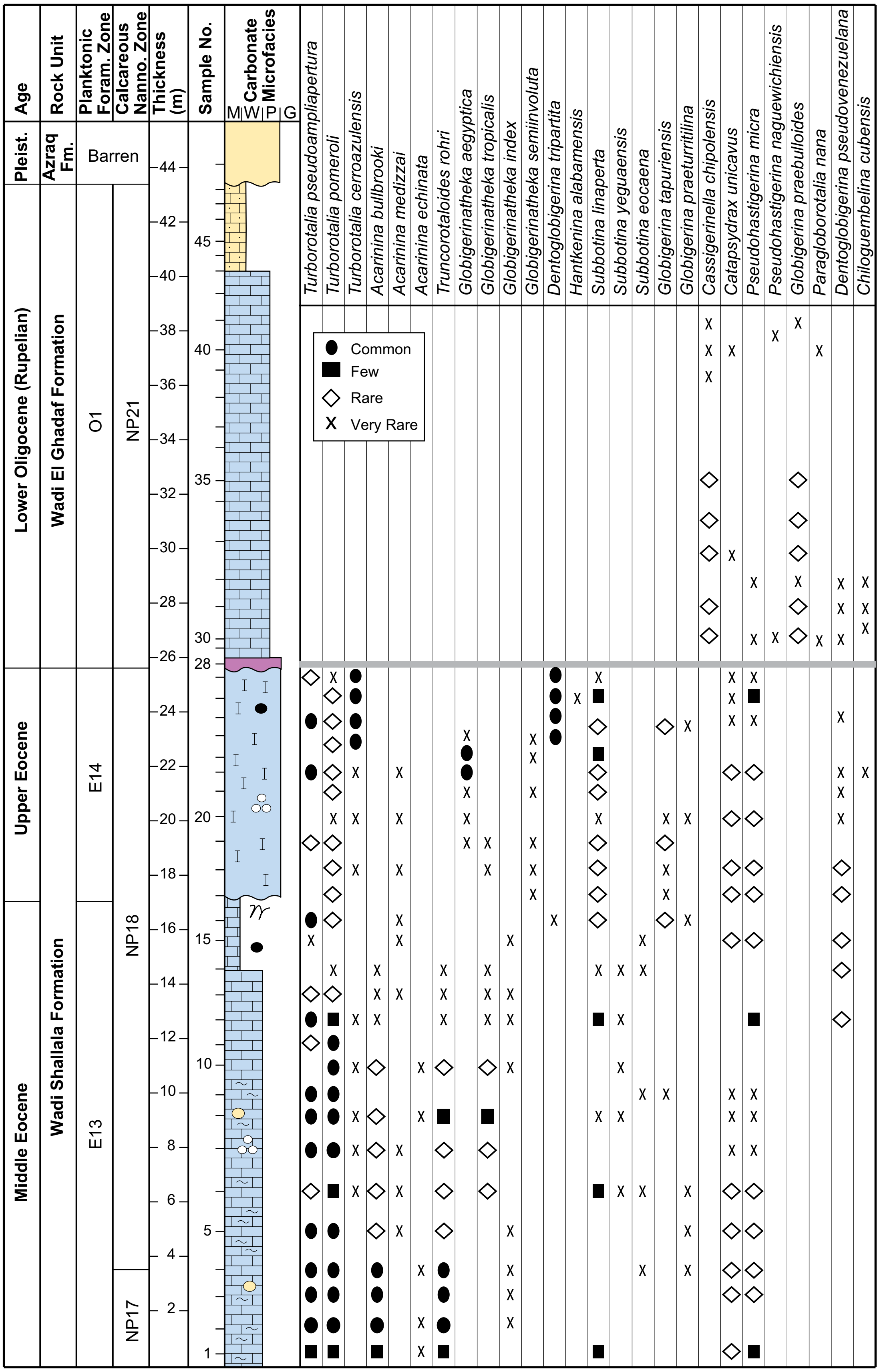


**Figure 7: Stratigraphic distribution of the identified planktonic foraminifera and biostratigraphic zones in the Qa' Faydat ad Dahikiya section. For symbol key see Figure 2.**

## INTEGRATED MICROPLANKTONIC BIOSTRATIGRAPHY

The correlation of the calcareous nannoplankton with the planktonic foraminiferal biostratigraphic zones for the Middle Eocene to Upper Oligocene differs from one author to another and from place to place as shown in Figures 8 and 9. According to Berggren and Pearson (2005), the *Discoaster saipanensis* (NP17) Zone is equivalent to the uppermost part of E12, and E13 and lower part of E14 zones, but according to Agnini et al. (2011) it is equivalent to the interval from the top part of E13 and lower part of E14 zones (Figure 9). Furthermore, the stratotype for the Middle/Upper Eocene boundary is still in the process of ratification.

Strougo (1992) suggested placing of Middle/Upper Eocene boundary in Egypt at the lowest occurrence of *Globigerinatheka semiinvoluta*, and in the case of the absence of *G. semiinvoluta*, the extinction of spinose planktonic foraminifera (*Acarinina*, *Truncorotaloides* and *Morozovelloides*), is suggested as an alternative criterion to denote the Middle/Upper Eocene boundary. The extinction level events of the muricate planktonic foraminifera have a much greater correlation potential worldwide, and have been taken by many authors to mark the Middle/Upper Eocene boundary in the tropical and Mediterranean regions (e.g. Toumarkine and Luterbacher, 1985; Haggag and Luterbacher, 1995; Haggag and Bolli, 1995; Wade et al., 2011, 2012). Several authors proposed recognition of the Middle/Upper Eocene boundary by means of calcareous nannofossils and place it at the NP17/NP18 boundary (e.g. Hardenbol and Berggren, 1978; Perch-Nielsen, 1985). Other authors (e.g. Proto Decima et al., 1975; Strougo, 2008; Strougo et al., 2013; Agnini et al., 2011, 2014) proposed to place it near the base Zone NP18, whereas Schaub (1981) placed it at the NP18/NP19 boundary. Abul-Nasr

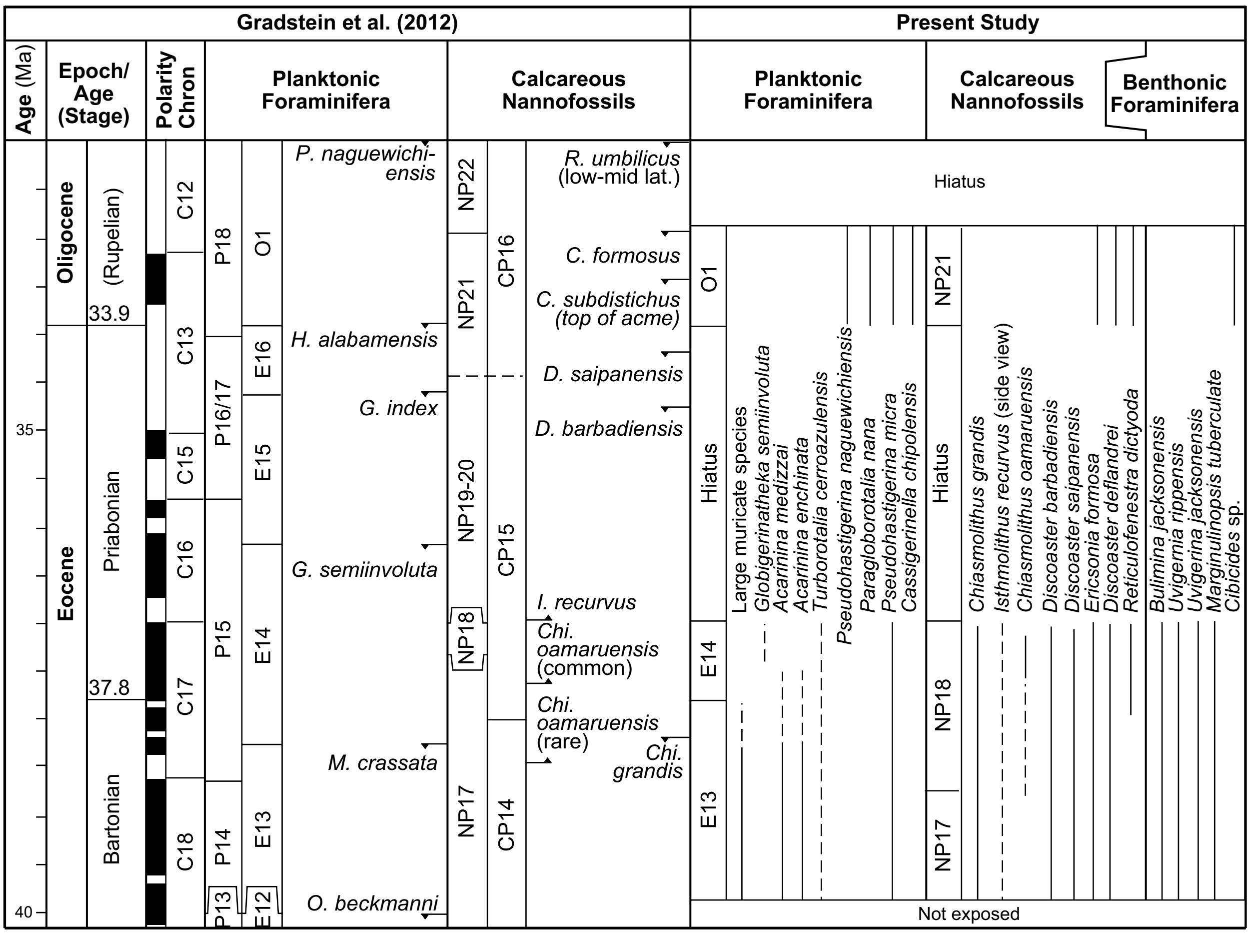


**Figure 8: Correlation between bioevents and zonations of Paleogene Time Scale of Gradstein et al. (2012) and the present study.**

and Marzouk (1994) reported the LO of *C. oamaruensis*, and hence the lower part of NP18 within the *Globigerinatheka semiinvoluta* Zone. However, Gradstein et al. (2012) placed the Middle/Upper Eocene boundary within the upper part of NP17 (Figure 8).

In the present study, the base of Zone NP18, which we have shown to be defined by LCO of *C. oamaruensis*, zonal marker NP18 occurs rarely in the upper part of Zone E13. It indicates the Middle Eocene, which is characterized by large muricate planktonic foraminifera (Figures 8 and 9). This criteria matches well with Strougo et al., (2013) but differs from Agnini et al. (2011) because they reported

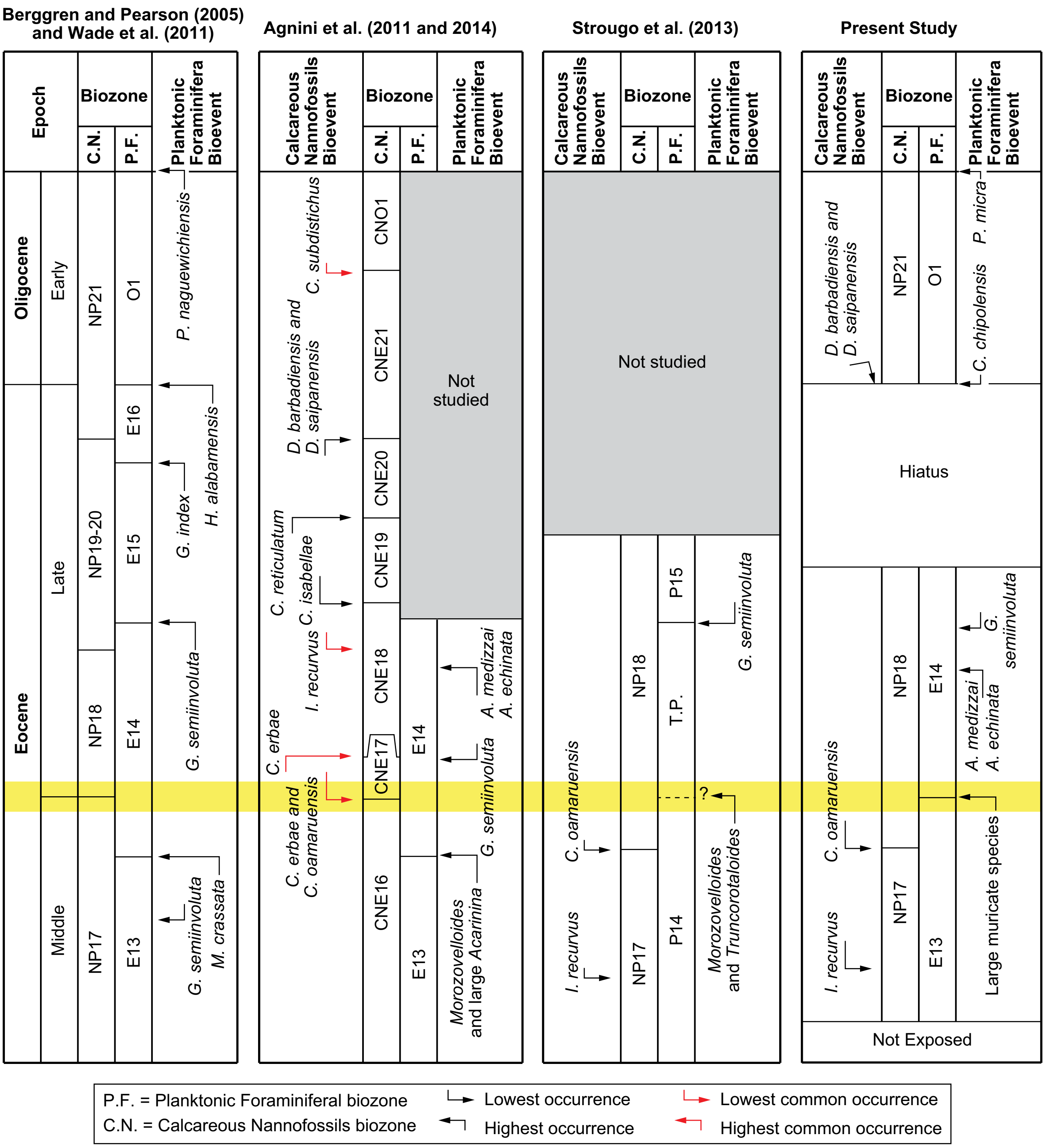


**Figure 9: Correlation between bioevents and zonations of different authors (the yellow line corresponds to the Middle/Upper Eocene boundary).**

the LO of *Chiasmolithus oamaruensis* above the extinction of large acarininids and *Morozovelloides*. Furthermore, Gradstein et al. (2012) noted the rare occurrence of *Chiasmolithus oamaruensis* in the Bartonian (Figure 8). Therefore, the authors believe that the *Chiasmolithus oamaruensis* LO datum is not a reliable stratigraphic marker for the Middle/Upper Eocene.

According to (Agnini et al., 2011, 2014), the Middle/Upper Eocene boundary lies somewhere within nannofossil Zone NP18, below the LO of *Globigerinatheka semiinvoluta* (Figure 9). On the other hand, many authors (e.g. Berggren and Miller, 1988; Berggren et al., 1995; Mancin et al., 2003; Luterbacher et al., 2004; Wade, 2004; Premoli Silva et al., 2006) reported the LO of *Globigerinatheka semiinvoluta* as a secondary marker because the LO of this taxon occurs slightly before the HO of muricate species in the Middle Eocene within the uppermost part of nannofossil Zone NP17. In this case, the LO of *Globigerinatheka semiinvoluta* should definitely be assigned to the Bartonian. Our results and correlations suggest that this boundary level, as defined by the LO of *Globigerinatheka semiinvoluta* defined in the Egypt and Italy, actually occurs slightly above the extinction of muricate planktonic foraminifera and corresponds to the earliest Late Eocene which falls in the higher part of NP18 nannofossil Zone 4 m above the HO of spinose and muricate species. It is clear that there is no sharp turnover in nannofossil taxa at this Middle/Upper Eocene boundary (i.e. within Zone NP18) and this boundary cannot be drawn precisely by means of calcareous nannofossils.

Many authors (e.g. Villa et al., 2008; Fornaciari et al., 2010; Strougo et al., 2013) have used the LCO of *C. oamaruensis*, to indicate the base of Zone NP18. In the present study, the LCO of *C. oamaruensis* has been found in sample interval D19 until D28, i.e. slightly above the extinction of large muricate planktonic foraminifera and, therefore, can be used as alternative bioevent to define the Middle/Upper Eocene boundary. A marked fall in relative sea level during the Middle/Late Eocene resulting from eustatic sea-level changes is associated with a sharp decrease in abundance of planktonic species and an increase in benthic foraminifera. This event can be correlated with the global cycle charts as recorded in Monferrato and Appenines, Italy by Mancin et al. (2003).

The extinction of *Discoaster saipanensis*, and *D. barbadiensis* occurred within the Late Eocene before the extinction of the *Turborotalia cerroazulensis* lineage (Agnini et al., 2011, 2014) while the base of the Oligocene is marked by LO of *Clausicoccus subdistichus* (= *Ericsonia subdisticha*). In the present study, the extinction of *Discoaster saipanensis*, and *D. barbadiensis* falls just below, or at, the Eocene/Oligocene unconformity, while the marker species *Clausicoccus subdistichus* (*Ericsonia subdisticha*) is absent. On the other hand, in terms of planktonic foraminifera the presences of *Paragloborotalia* and *Cassigerinella chipolensis* indicate an early Oligocene age.

## DISCUSSION

The Eocene/Oligocene boundary in Jordan is marked by a regional unconformity that is characterized by the absence of uppermost Eocene sediments. The timing of this depositional hiatus across different tectonic and sedimentary regimes within the northern Arabian Neo-Tethys realm can be attributed to the convergence of the Arabian Plate toward the Eurasia Plate throughout the Paleogene (Alsharhan and Nairn, 1995).

The Late Paleocene–Early Eocene active compression (Alpine Orogeny) caused frequent uplift and subsidence that deformed the Mesozoic strata along the northwest part of the Arabian Plate (Abu-Jaber et al., 1989; Ziegler, 2001). Tectonic events during the Paleogene resulted in the development of a local submarine topography of swells and basins in the southern Neo-Tethys area (Alsharhan and Nairn, 1997; Powell and Moh'd, 2011). These tectonic events also resulted in a change from high- to low-relative sea level (Ziegler, 2001). During the Late Eocene, parts of the Arabian Shelf and North Africa were uplifted into continental landmasses. Consequently, sediments recording the Early Oligocene global marine regression (Figure 5) are found only in portions of the shallow-marine realm that covered low-lying areas of the northern Africa and Arabian platforms (e.g. northern part of Egypt and Libya, Syria, north Iraq, Oman, United Arab Emirates).

In northwestern and eastern Jordan, Farouk et al. (2013) revealed an unexpected ca. 6.8 million year hiatus between the Middle Eocene and the Lower Oligocene sediments representing the absence of the Bartonian and Priabonian stages. In the present study, the upper part of the Bartonian is recorded indicating variable patterns of uplift and subsidence in the region during the development of the Eocene/Oligocene unconformity (Figure 5). Similar observations are recorded in Egypt, where the Upper Eocene–Oligocene deposits are recorded only in paleotopographic lows indicating the irregularity of the depositional basin, and a regional variation in tectonic activity during the Late Eocene–Oligocene period in the area of the north Arabian/African plates (Farouk et al., 2013).

Similarly, in the Negev, a correlative hiatus and the same variable pattern of a large magnitude unconformity across the Eocene/Oligocene boundary is observed with time gaps differing from place to place (Benjamini, 1984). Whittle et al. (1995) reported that during the Middle and Late Eocene times, a major regression took place associated with a large tectonic uplift in central Arabia exposing all of that area to extensive subaerial erosion. The development of a local submarine topography of swells and basins during the Early Oligocene has been demonstrated by Kuĉenjak et al. (2006) from widespread exploration wells localities in Syria. Nearby, in the Golan Heights, the equivalent Fiq Formation was assigned an Early Oligocene age based on the joint occurrence of *Pseudohastigerina micra* and *Cassigerinella chipolensis* (Michelson and Lipson Benitah, 1986). The Lower Oligocene marine faunas reported in this study from eastern Jordan, near the border with Saudi Arabia, indicate that a marine connection existed between the eastern and western provinces of the northern Neo-Tethys region.

The Eocene/Oligocene unconformity (disconformity) (Figure 2) represents a significant time gap of ca. 2.1 Myr duration with the absence of sediments of Late Priabonian age. The lowermost Oligocene bed (Unit 4) is a glauconized hardground with reworked lithoclasts comprising glauconitic and phosphatic lime mud, *in situ* ferruginous and phosphatic crusts, together with reworked phosphatized marine reptile bones, shark teeth and invertebrates. These lithologies and remanié fossils indicate a major phase of non-deposition characterized by winnowing of clasts and mineralization, the latter at or just below the sediment-water interface (Kennedy and Garrison, 1975; Jarvis, 1980; Jarvis et al., 2001). There are no indications of subaerial exposure of the basin at this time as might be deduced from indicators such as karstic surfaces or oxidative reddening (e.g. red paleosols).

Similar burrowed and mineralized submarine hardground surfaces are present at a number of major formation and sequence boundaries during deposition of the latest Cretaceous to Paleogene successions in the region (Powell, 1989; Powell and Moh'd, 2011, 2012) (e.g. top of the Muwaqqar Chalk Marl (Maastrichtian–Paleocene); top of the Umm Rijam Chert Limestone (Eocene). These mineralized firmgrounds and hardgrounds such as the lowermost Wadi El Ghadaf Formation (Unit 4) described here, represent a period of non-deposition within a pelagic shelf setting, whereby early submarine cementation, corrosion of the carbonate substrate and reworking/winnowing of intraclasts and fossils took place in a localized redox environment conducive to the formation of glauconite and ferruginous crusts.

We interpret this period of non-deposition and submarine erosion at the Eocene/Oligocene boundary in the Qa' Faydat ad Dahikiya area as a result of changes in oceanic circulation in the Neo-Tethys Ocean that was associated with gentle intraplate deformation of the northern Arabian Plate (Cloetingh, 1988; Chaimov et al., 1992) rather than major subaerial uplift and resulting terrestrial erosion.

## CONCLUSIONS

At Qa' Faydat ad Dahikiya area, near the Jordan-Saudi Arabia border, a succession of Upper Paleogene sediments that record the Middle/Upper Eocene to Lower Oligocene transition are well exposed and widely distributed. The basal part of this succession (Wadi Shallala Formation) is characterized by a large assemblage of muricate planktonic foraminiferal species (e.g. *Truncorotaloides* and *Acarinina* spp.) and the complete absence of *Morozovelloides* that indicate the upper part of Middle Eocene age (Zone E13), while the equivalent nannofossils indicate Zone NP17 based on the absence of *Chiasmolithus solitus* and *Chiasmolithus oamaruensis* in the basal part of the examined section.

The Middle/Upper Eocene boundary has often proved difficult to determine in the Neo-Tethys area, and has significantly hampered the correlation of microplanktonic bioevents, because the age of lowest occurrence (LO) and highest occurrence (HO) species differ from place to place. The lowest occurrence (LO) of *Isthmolithus recurvus* is confirmed here as an unreliable marker because it is found along with large muricate species within Zone E13 (Middle Eocene) and, therefore, cannot be used to define the top Zone NP18. The Middle/Upper Eocene boundary has traditionally been recognized in planktonic foraminiferal biostratigraphy above the extinction of whole spinose and large muricate species, which occurs within the calcareous nannofossil Zone NP18 and below LO of *Globigerinatheka semiinvoluta*. The small sized *A. medizzai* are low in abundance and not consistently present in the earliest Late Eocene. In fact, the LO of *Globigerinatheka semiinvoluta*, is not considered a reliable marker for global correlation, but may be a useful correlative species in the Middle East. Therefore, the authors prefer to use the extinction of muricate groups to define the Zone E14 and hence the Middle/Upper Eocene boundary. A significant interval that coincides with the well-known sea-level fall between the Middle and Late Eocene is recorded in the present study between the extinction of the muricate and spinose forms and the LO of *Globigerinatheka semiinvoluta*.

The Eocene/Oligocene boundary in Jordan and the surrounding region is marked by a major unconformity (disconformity) that differs in magnitude from place to place due to the variable intraplate structural deformation across the northern Arabian Plate during early regression of Neo-Tethys during the Oligocene. Consequently, shallow-marine sediments were deposited only in areas of submarine paleo-lows. The duration of the depositional hiatus and unconformity is estimated at ca. 2.1 Myr, and is based on the absence of the planktonic foraminifera zones E15 and E16 and absence of the coeval calcareous nannofossil Zone NP19 until lower part of Zone NP21. A remarkable turnover in microplanktonic assemblages is observed across the Eocene/Oligocene unconformity, as indicated by sharp decline in the species diversity and disappearances and appearances of many nannofossil taxa.

The burrowed, mineralized hardground immediately above the unconformity, which includes reworked lithoclasts and fossils, is interpreted as a lowstand and depositional hiatus on the sea floor that resulted in glauconitic and ferruginous mineralization. The Early Oligocene represents a renewed phase of transgression and marine flooding in the region following a major depositional hiatus, culminating in a regressive phase of siliciclastic clastic sedimentation that marks the demise of the Neo-Tethys Ocean.

The presence of Lower Oligocene marine sediments in eastern Jordan indicates that communication between the eastern and western provinces of the Neo-Tethys region still existed at that time. Correlation with other areas in the Middle East has revealed that the Eocene/Oligocene unconformity is present in nearly all countries.

## APPENDIX

Alphabetic list of calcareous nannofossil and foraminiferal species mentioned in the paper.

### (A) Calcareous nannofossils

*Blackites tenuis* Bramlette and Sullivan (1961)
*Chiasmolithus grandis* (Bramlette and Riedel, 1954) Radomski (1968)
*Chiasmolithus oamaruensis* (Deflandre, 1954) Hay, Mohler and Wade (1966)
*Chiasmolithus solitus* (Bramlette and Sullivan, 1961) Locker (1968)
*Coccolithus pelagicus* (Wallich, 1877) Schiller **(**1930)
*Cribrocentrum reticulatum* (Gartner and Smith, 1967) Perch-Nielsen (1971)
*Cribrocentrum erbae* Fornaciari et al., (2010)
*Cribrocentrum isabellae* Fornaciari et al., (2010)
*Coronocyclus nitescens* (Kamptner, 1963) Bramlette and Wilcoxon (1967)
*Coronocyclus bramlettei* (Hay Towe, 1962) Bown (2005)
*Cyclicargolithus floridanus* (Roth and Hay *in* Hay et al. 1967) Bukry (1971)
*Dictyococcites bisectus* (Hay, Mohler and Wade, 1966) Bukry and Percival (1971)

*Discoaster barbadiensis* Tan (1927)
*Discoaster deflandrei* Bramlette and Riedel (1954)
*Discoaster saipanensis* Bramlette and Riedel (1954)
*Discoaster tanii* Bramlette and Riedel (1954)
*Ericsonia subdisticha* (Roth and Hay in Hay et al., 1967) Roth in Baumann and Roth, 1969
*Ericsonia formosa* (Kamptner, 1963) Haq (1971)
*Helicosphaera bramlettei* Muller (1970)
*Helicosphaera compacta* Bramlette and Wilcoxon (1967)
*Helicosphaera lophota* Bramlette and Sullivan (1961)
*Helicosphaera reticulata* Bramlette and Wilcoxon (1967)
*Isthmolithus recurvus* Deflandre (1954)
*Lanternithus minutus* Stradner (1962)
*Neococcolithes dubius* (Deflandre, 1954) Black (1967)
*Neococcolithes minutus* (Perch-Nielsen, 1967) Perch-Nielsen (1971)
*Pontosphaera exilis* (Bramlette and Sullivan, 1961) Romein (1979)
*Pontosphaera multipora* (Kamptner, 1948) Roth (1970)
*Pontosphaera pectinata* (Bramlette and Sullivan, 1961) Sherwood (1974)
*Pontosphaera plana* (Bramlette and Sullivan, 1961) Haq (1971)
*Pontosphaera versa* (Bramlette and Sullivan, 1961) Sherwood (1974)
*Reticulofenestra dictyoda* (Deflandre *in* Deflandre and Fert, 1954) Stradner *in* Stradner and Edwards (1968)
*Reticulofenestra hampdenensis* Edwards (1973)
*Reticulofenestra hillae* Bukry and Percival (1971)
*Reticulofenestra umbilica* (Levin, 1965) Martini and Ritzkowski (1968)
*Sphenolithus moriformis* (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon (1967)
*Scyphosphaera apsteinii* Lohmann (1902)
*Zygrhablithus bijugatus* (Deflandre *in* Deflandre and Fert, 1954) Deflandre (1959)

## (B) Planktonic foraminifera

*Acarinina bullbrooki* (Bolli, 1957)
*Acarinina echinata* (Bolli, 1957)
*Acarinina medizzai* (Toumarkine and Bolli, 1975)
*Cassigerinella chipolensis* (Cushman and Ponton, 1932)
*Catapsydrax unicavus* Bolli, Loeblich and Tappan, 1957
*Chiloguembelina cubensis* (Palmer, 1934)
*Dentoglobigerina pseudovenezuelana* (Blow and Banner, 1962)
*Dentoglobigerina tripartita* (Koch, 1926)
*Globigerina praebulloides* Blow, 1959
*Globigerina praeturritilina* Blow and Banner, 1962
*Globigerina tapuriensis* Blow and Banner, 1962
*Globigerinatheka aegyptica* (Haggag and Bolli, 1995)
*Globigerinatheka index* (Finlay, 1939)
*Globigerinatheka semiinvoluta* (Keijzer, 1945)
*Globigerinatheka tropicalis* (Blow and Banner, 1962)
*Hantkenina alabamensis* Cushman, 1925
*Orbulinoides beckmanni* (Saito, 1962)
*Paragloborotalia nana* (Bolli, 1957)
*Pseudohastigerina micra* (Cole, 1927)
*Pseudohastigerina naguewichiensis* (Myatliuk, 1950)
*Subbotina eocaena* (Guembel, 1868)
*Subbotina linaperta* (Finlay, 1939)
*Subbotina yeguaensis (*Weinzierl and Applin, 1929)
*Truncorotaloides rohri* Brönnimann and Bermudez, 1953
*Turborotalia cerroazulensis* (Cole, 1928)
*Turborotalia pomeroli* (Toumarkine and Bolli, 1970)
*Turborotalia pseudoampliapertura* (Blow and Banner, 1962)

## (C) Benthic foraminifera

*Bulimina jacksonensis* Cushman, 1925
*Cibicides* sp.
*Marginulinopsis tuberculate* (Plummer, 1927)
*Uvigerina rippensis* Cole, 1927
*Uvigerina jacksonensis* Cushman, 1925

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