

Integrated biostratigraphy of two Upper Maastrichtian – Palaeocene successions in north-central Sinai, Egypt



Mahmoud Faris¹ and Sherif Farouk²

¹ Geology Department, Faculty of Science, Tanta University, Egypt, mhmfaris@yahoo.com

² Egyptian Petroleum Research Institute, Nasr City, 11727, Egypt, geo.sherif@hotmail.com

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ABSTRACT

Integration of the calcareous nannofossil and planktonic foraminiferal biostratigraphies has been performed for the Upper Maastrichtian – Palaeocene successions at Gebel Umm Khushayb and west El-Hassana sections (north-central Sinai, Egypt). The studied successions include the uppermost part of the Sudr, Dakhla, and Tarawan formations and their lateral coeval Beida Formation. Biostratigraphic analysis has allowed recognition from Zone CF2 to Zone P4 in terms of planktonic foraminifera and from Zone CC26c to Zone NP7/8 in terms of calcareous nannofossils. The Maastrichtian/Palaeogene (K/Pg) boundary is characterized by an erosional surface that marks a hiatus between the Sudr/Dakhla or Sudr/Beida formation boundaries, as confirmed by the absence of the planktonic foraminiferal CF1 to P1a zones and their equivalent nannofossil zones (top part of CC26c to lowest part of Zone NP3). The Danian/Selandian (Da/Se) boundary lies in the upper part of the Dakhla Formation within the top of nannofossil Zone NP4, and within planktonic foraminiferal Zone P3b, similar to that of the Global Standard Stratotype-section and Point (GSSP) of the D/S boundary which has recently been chosen at the Zumaia section, northern Spain. A minor hiatus was observed across the Selandian/Thanetian boundary as indicated by a lithological change and a very condensed Zone NP6, corresponding to the Dakhla and Tarawan formation boundary in the west El-Hassana section.

Keywords: biostratigraphy, calcareous nannofossils, Danian/Selandian boundary, planktonic foraminifera, north-central Sinai.

1. INTRODUCTION

The Palaeocene successions in Egypt are marked by widely distributed, condensed successions rich in calcareous planktonic faunal assemblages with distinct vertical and lateral facies changes. A considerable number of previous papers deal with the biostratigraphy of the Palaeocene of Sinai (e.g. LÜNING et al., 1998; MARZOUK & LÜNING, 1998; EL-NADY & SHAHIN, 2001; SAMIR, 2002; AYYAD et al.,

2003; SPEIJER, 2003; AL-WOSABI & ABU SHAMA, 2007; FARIS & SALEM, 2007; FARIS & ABU SHAMA, 2007; FAROUK & FARIS, 2008). The present study provides the first information on the biostratigraphy at Gebel Umm Khushayb and only a few small works have been undertaken on the El-Hassana area (EL-DEEB et al., 2000 & FARIS et al., 2000). These authors placed the Palaeocene stage boundaries according to older concepts (before defini-

tion of the global stratotypes of the Danian/Selandian and Selandian/Thanetian boundaries). In the two study sections, the K/Pg, De/Se and Se/Th remain unclear and not been precisely identified.

However, many discrepancies in the Palaeocene bio-events could not be clarified because either taxonomically different concepts caused uncertainties in correlation of the Palaeocene zones, especially in the southern Tethyan realm, (ORUE-ETXEBARRIA et al., 2007; ARENILAS, 2012), or these marker bio-events are recorded from different palaeolatitudes showing considerable variations in age (FAROUK & FARIS, 2011).

The main purpose of this research was to accurately correlate the Palaeocene bio-events with the standard biostratigraphic scales, using both calcareous nannofossils and planktonic foraminifera, for two Upper Maastrichtian – Palaeocene successions in north-central Sinai, and to discuss in details the Cretaceous/Palaeogene (K/Pg), the Danian/Selandian (Da/Se) and the Selandian/Thanetian (Se/Th) boundaries in the studied successions.

2. MATERIALS AND METHODS

Seventy-six rock samples were collected, approximately every 25–50 cm from the two studied sections at Gebel Umm Khushayb (30°14'27"N and 33°13'33"E) and west El-Hasana (30°25'40"N and 33°46'41"E), (Fig. 1).

Calcareous nannofossils were analyzed using standard smear slides, which were examined using a light photomicroscope at 1250X magnification. A qualitative estimation of the abundance of calcareous nannofossil taxa are noted as follows: A= abundant (more than 5 specimens /field of view, fov), C=common (1–5 specimens/fov), F=frequent (one

specimen /2–5 fov), R= rare (one specimen/6–10 fov) and VR=very rare (one specimen/ more than 10 fov).

For the planktonic foraminifera, about 200g of dry rock samples were disaggregated in water and washed through a 63µm sieve. The relative abundance of planktonic foraminiferal taxa are defined as follows: abundant, >26%; common, 16–25%; few, 6–15%; rare, 2–5%; very rare, <2%.

3. GEOLOGICAL SETTING AND LITHOSTRATIGRAPHY

Tectonically, SAID (1962) divided Egypt into two major provinces, the deformed Unstable Shelf to the north, and the nearly horizontal and less deformed Stable Shelf to the south (Fig. 1). The Syrian Arc Fold Belt is one of the best-known structural features in the Unstable Shelf, and it played an important role in controlling the configuration of the depositional sequences and the great complexity of changes both in facies and thickness (FAROUK & FARIS, 2008). The study area lies in north-central Sinai of the Unstable Shelf and is characterized by complex uplifts and domal anticlines of the Syrian Arc Fold Belt, that were formed during the closure of Neo-Tethys during the convergence of the African-Arabian Craton (STAMPFLI et al., 1995).

Maastrichtian – Palaeocene siliciclastic/carbonate outcrops are widely distributed in north-central Sinai, where the Campanian-Maastrichtian Sudr Formation overlies unconformably the Palaeocene sediments, which correspond to four well-defined formations from oldest to youngest are; Dakhla Formation, Tarawan Formation and lowermost part of the Esna Formation and their lateral coeval Beida Formation. The following is a detailed lithostratigraphic description of the detected Upper Maastrichtian – Palaeocene formations in the study area, given from older to younger (Fig. 2).

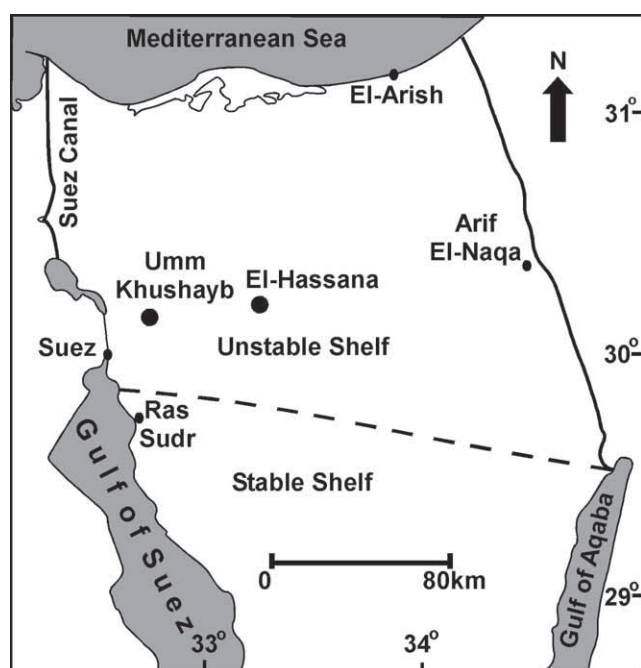


Figure 1: Location map of the study area.

Sudr Formation- Campanian-Maastrichtian

The Campanian-Maastrichtian Sudr Formation (GHORAB, 1961) is widespread throughout the foot slopes of Sinai. It unconformably overlies the Dakhla or Bedia formations with a sharp lithological contact. The Sudr Formation is subdivided from base to top into the Markha and Abu Zenima members. The study measured part of the Sudr Formation deals only with the uppermost part of Abu Zenima Member (Upper Maastrichtian). It consists of argillaceous limestone with a measured thickness of about 2–2.5 m in the study sections (Fig. 2).

Dakhla Formation- Danian-Selandian

The term Dakhla Formation was firstly used by SAID (1961) to describe the Maastrichtian-Palaeocene siliciclastics and carbonate deposits in Dakhla Oasis, Western Desert. In northern latitudes 26°30' in Egypt, the lower part of the Dakhla Formation is generally laterally equivalent to carbonate facies (the Sudr and Khoman formations).

Therefore in the Sinai Peninsula, the Dakhla Formation belongs to the Palaeocene and it overlies unconformably the

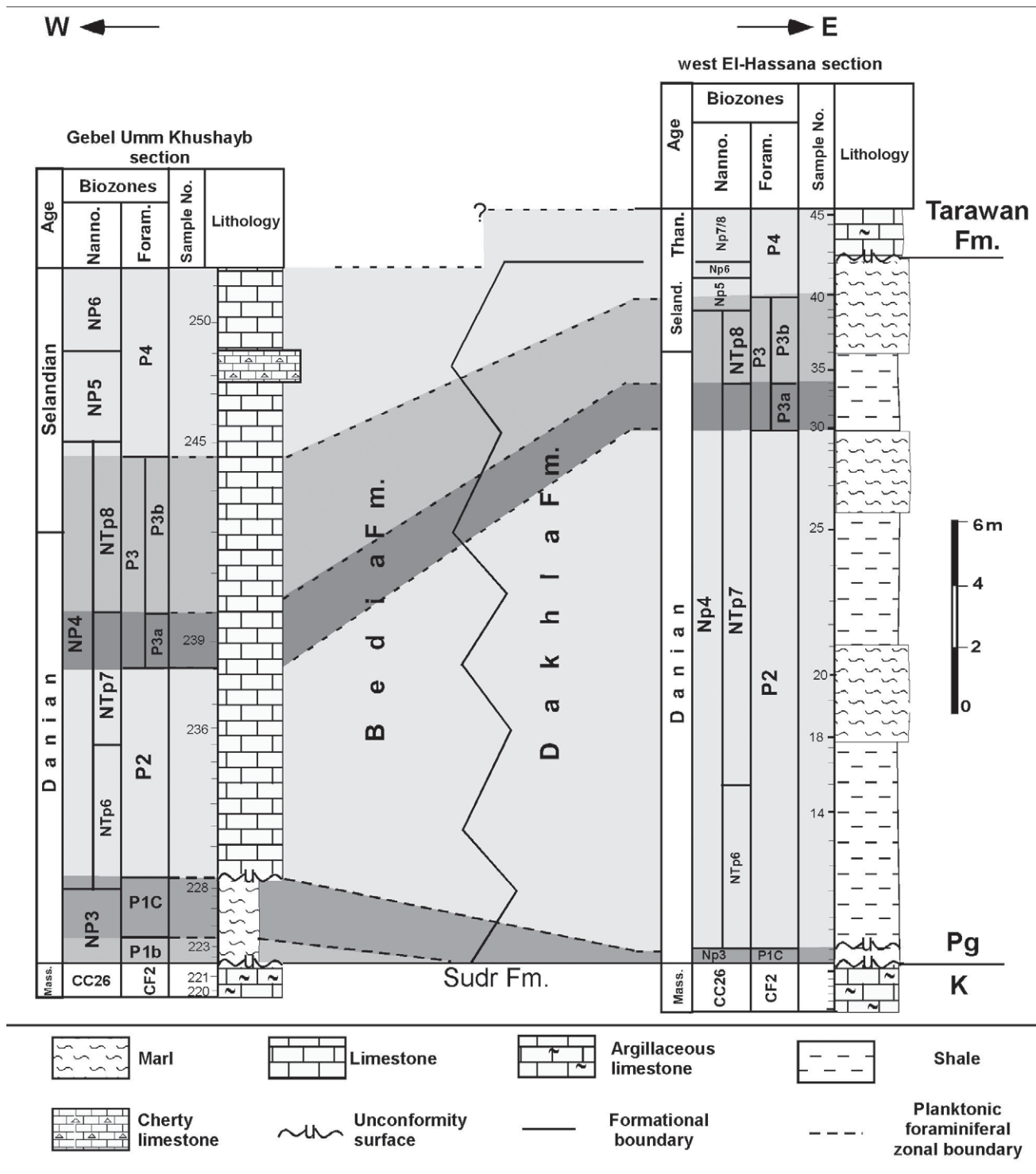


Figure 2: Stratigraphic correlation of the studied sections in the north-central Sinai. Calcareous nannofossil schemes are after MARTINI (NP, 1971) and VAROL (NTp, 1989) and SISSIGH (CC, 1977). Planktonic foraminiferal schemes are after BERGGREN & PEARSON (P, 2005).

Maastrichtian Sudr Formation and also underlies the Tarawan Formation, with very clear contact, and can be easily recognized in the field. It consists mainly of moderately hard, greenish grey monotonous pelagic calcareous mudstone with flooded well-diversified calcareous planktonic assemblages with thicknesses ranging from 20 to 25 m in the west El-Hassana section.

Tarawan Formation- Thanetian

The Tarawan Formation (AWAD & GHOBRIAL, 1965) is composed of hard to moderately hard, massive yellowish white argillaceous limestone, partly limonitic with a thickness of 2 to 4 m in the west El-Hassana section. The partly resistant, light-coloured limestone of this unit is clearly distinguished from the overlying and underlying dark-colored

soft shales. In Egypt, the Dakhla Formation is overlain by the Tarawan Formation which includes, at its upper part, the so-called “*Velascoensis* Event” with notable changes in the patterns of sedimentation in late Palaeocene time. The event that produced those changes is believed to be primarily tectonic coupled with global sea-level fall (STROUGO, 1986).

Beida Formation- Palaeocene

The term Beida Formation was firstly used by ALLAM & KHALIL (1988) based upon predominant carbonate deposits at Wadi Beida, north of Gebel Arif El-Naqa. It is equivalent to the Palaeocene siliciclastic/carbonate of the Esna Formation, which is recorded in different parts of Egypt.

In the study area, the Beida Formation has a wide distribution in the submerged palaeo-high areas around central Sinai, extending from Gebel Umm Khushayb to Ras Sudr. It unconformably overlies and underlies the Sudr and Thebes formations, respectively. The Beida Formation attains a total thickness of 40 m and is composed of greenish gray marl, argillaceous limestone, and well-bedded chalky limestone with chert bands in the Gebel Gebel Umm Khushayb section.

4. BIOSTRATIGRAPHY

The biostratigraphy is evaluated here based on the Cretaceous Foraminiferal (CF) Zonal Scheme of LI & KELLER (1998) and on the Palaeocene (P) Zonal Scheme of BERGGERN & PEARSON (2005). These zonal schemes are applied in the present study to provide a much improved biostratigraphic framework.

For the calcareous nannofossil zonation, the Cretaceous Zonal Scheme of SISSINGH (1977) and the Palaeogene Zonal Scheme of MARTINI (NP, 1971) and VAROL (NTp, 1989) have been applied. The distribution of the calcareous nannofossils and planktonic foraminifera in the two studied sections are shown in Tables 1–4. The most important foraminifera and calcareous nannofossil taxa are figured in three plates (1–3). Abbreviations used FO= First Occurrence,

LO= Last Occurrence; FCO= First Common Occurrence; FRO= First Rare Occurrence. The following is the description of the established calcareous nannofossil and planktonic foraminiferal biozones arranged from older to younger.

4.1. Calcareous nannofossils

4.1.1. *Micula prinsii* Subzone (CC26c)

Definition: The *Micula prinsii* Subzone is defined as the interval from the FO of *Micula prinsii* Perch-Nielsen to the increased frequency of *Thoracosphaera operculata* Bramlette & Martini.

Occurrence: This zone occupied the upper most part of the Sudr Formation and is represented by samples 220–221 (2 m thick) in Umm Khushayb; and samples 1–6 in west El-Hassana (2.5 m thick).

Characteristic species: The most important taxa also identified from this subzone are: *Ahmullerella octoradiata* (GORKA), *Arkhangelskiella cymbiformis* VEKSHINA, *Chiastozygus amphipons* (BRAMLETTE & MARTINI), *Stradneria crenulata* (BRAMLETTE & MARTINI), *Cribrosphaerella ehrenbergii* (ARKHANGELSKY), *Cyclagelosphaera reinhardtii* (PERCH-NIELSEN), *Eiffellithus gorkae* Reinhardt, *Lithraphidites quadratus* BRAMLETTE & MARTINI, *Lucianorhabdus cayeuxii* DEFLANDRE, *Manivitella pemmatoidea* (DEFLANDRE in MANIVIT), *Microrhabdulus decoratus* DEFLANDRE, *Micula decussata* VEKSHINA, *Zygodiscus crux* (DEFLANDRE & PERT), and others (Tables 1 & 2). Rare specimens of *M. murus* (MARTINI) and *M. prinsii* PERCH-NIELSEN are recorded in the topmost part of the Sudr Formation in the studied sections.

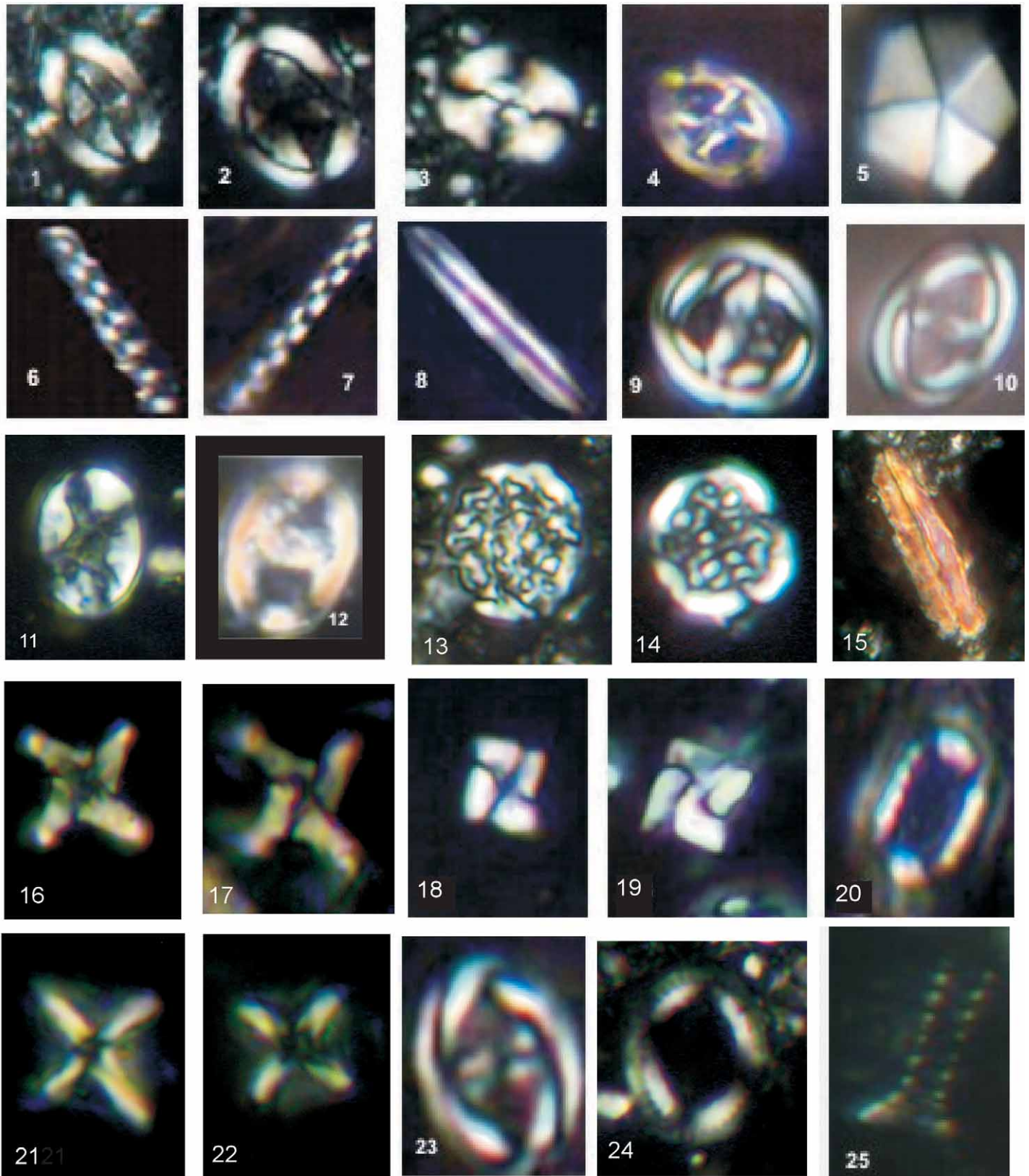
Remarks: The *Micula prinsii* Subzone was informally defined by PERCH-NIELSEN (1979) and corresponds to the upper part of Zone CC26 of SISSINGH (1977). This subzone is a correlative of the latest Maastrichtian. However, its upper limit cannot be determined with accuracy in the two studied sections due to a large hiatus observed at the base of the Palaeocene.

Plate 1

- 1–2 *Arkhangelskiella cymbiformis* VEKSHINA, 1959, sample 2, west El-Hassana section.
- 3 *Watznaueria barnesae* (BLACK in BLACK & BARNES, 1959), sample 221, Gebel Umm Khushayb section.
- 4 *Chiastozygus amphipons* (BRAMLETTE & MARTINI, 1964), sample 4, west El Hassana section.
- 5 *Braarudosphaera bigelowii* (GRAN & BRAARUD, 1935), sample 3, west El Hassana section.
- 6–7 *Microrhabdulus decoratus* DEFLANDRE, 1959, sample 221, Gebel Umm Khushayb section.
- 8 *Lithraphidites carniolensis* DEFLANDRE, 1963, sample No.5, west El-Hassana section.
- 9–10 *Placozygus sigmoides* (BRAMLETTE & SULLIVAN, 1961), sample 32, west El-Hassana section.
- 11 *Eiffellithus gorkae* REINHARDT (1965), sample 220, Gebel Umm Khushayb section.
- 12 *Zeugrhabdulus pseudanthophorus* (BRAMLETTE & MARTINI, 1964), sample 3, west El-Hassana section.
- 13 *Thoracosphaera operculata* BRAMLETTE & MARTINI, 1964, sample 228, Gebel Umm Khushayb section.
- 14 *Thoracosphaera saxea* STRADNER, 1961, sample 12, west El-Hassana section.
- 15 *Lucianorhabdus cayeuxii* DEFLANDRE, 1959, sample 220, Gebel Umm Khushayb section.
- 16–17 *Micula prinsii* PERCH-NIELSEN, 1979, sample 1, west El-Hassana section.
- 18–19 *Micula murus* (MARTINI, 1961), sample 2, west El-Hassana section.
- 20 *Cribrosphaerella ehrenbergii* (ARKHANGELSKY, 1912), sample 221, Gebel Umm Khushayb section.
- 21–22 *Micula decussata* VEKSHINA, 1959, sample 222, Gebel Umm Khushayb section.
- 23 *Zygodiscus spiralis* BRAMLETTE & MARTINI, 1964, sample 4, west El-Hassana section.
- 24 *Manivitella pemmatoidea* (DEFLANDRE in MANIVIT, 1965), sample 221, Gebel Umm Khushayb section.
- 25 *Tetrapodorhabdus decorus* (DEFLANDER in DEFLANDER & FERT, 1954), sample 5, west El-Hassana section.

Micula murus is one of the rare Maastrichtian species and clearly restricted to low latitudes (WORSLEY AND MARTINI, 1970; THIERSTEIN, 1981; GARDIN, 2002; LEES,

2002). It was used for recognition of the uppermost Maastrichtian (LAMOLDA & GOROSTIDI, 1992; POSPICAL, 1994; BERNAOLA & MONECHI, 2007 and many others).



10µm 

4.1.2. *Chiasmolithus danicus* Zone (NP3)

Definition: The *Chiasmolithus danicus* Zone is defined as the interval from the FO of *Chiasmolithus danicus* (BROTZEN) to the FO of *Ellipsolithus macellus* (BRAMLETTE & SULLIVAN).

Occurrence: This zone occupied the lowermost part of the Dakhla and Bedia formations and is represented by samples 222–227 (2.5 m thick) in Umm Khushayb; and samples 7–8 in west El-Hassana (0.2 m thick).

Characteristic species: The most characteristic species of this zone are: *Cruciplacolithus tenuis* (STRADNER), *C. primus* PERCH-NIELSEN, *Ericsonia subpertusa* HAY & MOHLER, *E. cava* (HAY & MOHLER) and *Coccolithus pelagicus* (WALLICH).

Remarks: The vanishing Cretaceous species are those extinct at the K/Pg boundary, and the Cretaceous persistent species are those calcareous nannofossil genera and species that are known to occur in the Cretaceous and survive into the Palaeocene (PERCH-NIELSEN, 1985b). The NP3 Zone is characterized by a decrease of Cretaceous vanishing species. In the two studied sections, Cretaceous persistent species are very rare in this zone and only a few specimens of *Thoracosphaera operculata* BRAMLETTE & MARTINI, *Placozygus sigmoides* (BRAMLETTE & SULLIVAN) and *Cyclagelosphaera reinhardtii* (PERCH-NIELSEN) dominate the assemblage. This zone has a reduced thickness in both the studied sections. *Cruciplacolithus edwardsii* ROMEIN first appears simultaneously with the FO of *Ch. danicus* (base NP3).

The identified Zone NP3 is equivalent to Zone NP3 of MARTINI (1971), the upper part of the *Cruciplacolithus tenuis* Zone of ROMEIN (1979), the CP2 Zone of OKADA & BUKRY (1980), FARIS & ABU SHAMA (2007) and FARIS & SALEM (2007).

4.1.3. *Ellipsolithus macellus* Zone (NP4)

Definition: The FO of *Ellipsolithus macellus* (BRAMLETTE & SULLIVAN) is used to define the base of Zone NP4, and the FO of *Fasciculithus tympaniformis* HAY & MOHLER defined its top (MARTINI, 1971).

Occurrence: This zone occupied the middle part of the Dakhla and Bedia formations, represented by samples 228–244 (14.5m thick) in Umm Khushayb; and samples 9–39 in West El-Hassana (19 m thick).

Characteristic species: The FOs of *Fasciculithus ulii* PERCH-NIELSEN, *F. billii* PERCH-NIELSEN, *F. bitectus* ROMEIN, *F. pileatus* BUKRY, *F. involutus* BRAMLETTE & SULLIVAN and *F. jani* PERCH-NIELSEN occur within the Zone NP4 in the two study sections.

Remarks: According to the Palaeocene zonation of VAROL (1989), the Zone NP4 in west El-Hassana and Umm Khushayb sections can be divided into three subzones, NTP6, NTP7 and NTP8. VAROL (1989) subdivided Zone NTP7 and NTP8 into several subzones. In the present study, it was so difficult to subdivide these two biozones into several subzones due to the extreme condensation of this interval. On the other hand, Zone NP4 could be divided into two subzones; NP4a, *Ellipsolithus macellus-Sphenolithus primus* Subzone, it is defined from the FO of *E. macellus* (BRAMLETTE & SULLIVAN) to the FO of *Sphenolithus primus* PERCH-NIELSEN and NP4b, *Sphenolithus primus-Fasciculithus tympaniformis* defines from the FO of *Sphenolithus primus* to the FO of *Fasciculithus tympaniformis* (QUILLÉVÉRÉ et al., 2002 and FARIS et al., 2005). This subdivision was applied in the current study.

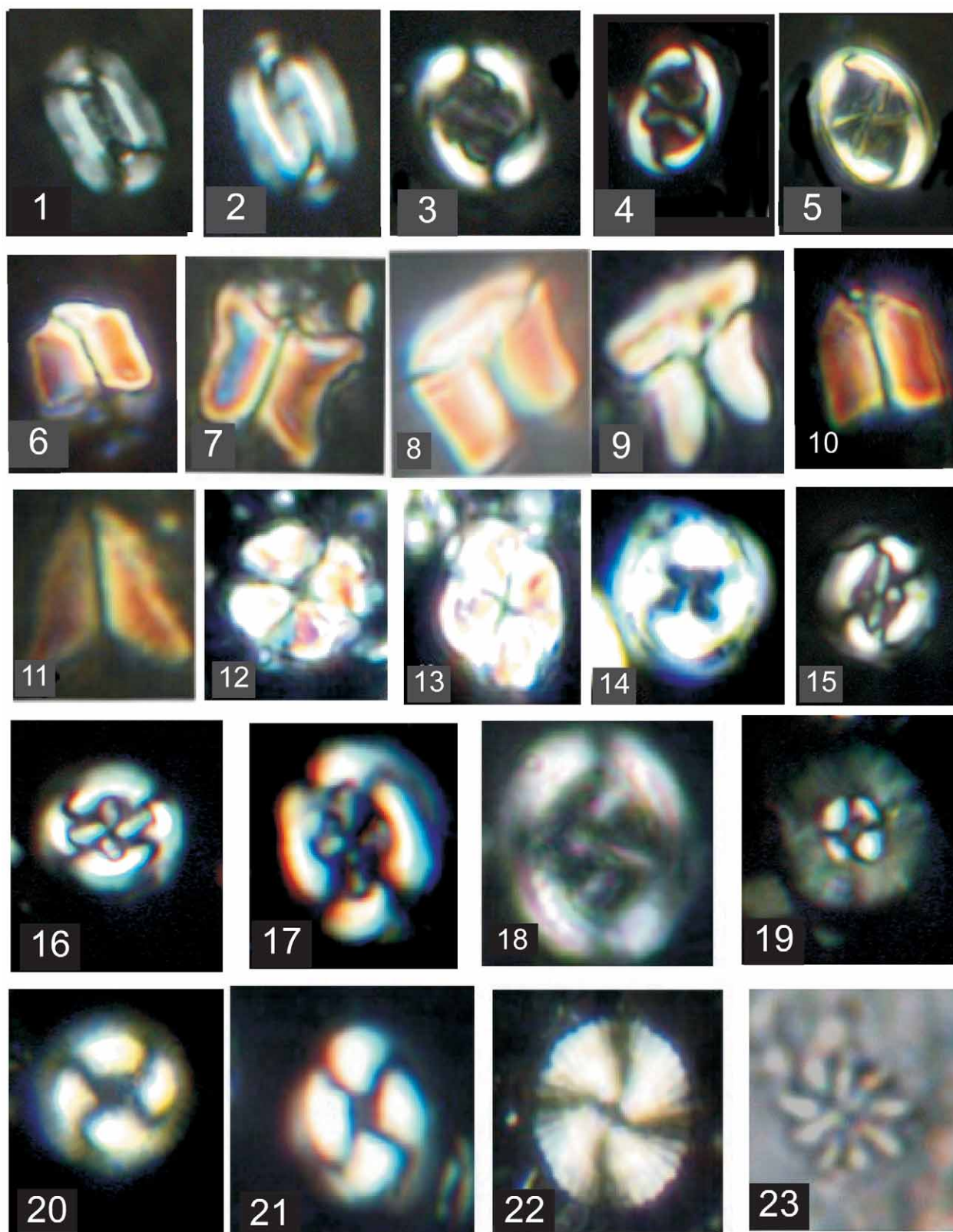
A small hiatus is suggested at the NP3/NP4 zonal boundary in the two studied sections, based on the absence of the uppermost part of Zone NP3 and the basal part of

Plate 2

- 1–2 *Ellipsolithus macellus* (BRAMLETTE & SULLIVAN, 1961), sample 9, west El-Hassana section.
- 3 *Chiasmolithus edentulus* VAN HECK & PRINS, 1987, sample 22, west El-Hassana section.
- 4 *Neochiastozygus perfectus* PERCH-NIELSEN, 1971, sample 247, Gebel Umm Khushayb section.
- 5 *Neochiastozygus junctus* (BRAMLETTE & SULLIVAN, 1961), sample 242, Gebel Umm Khushayb section.
- 6 *Fasciculithus tympaniformis* HAY & MOHLER in HAY et al., 1967, sample 40, west El-Hassana section.
- 7 *Fasciculithus billii* PERCH-NIELSEN, 1971, sample 42, west El-Hassana section.
- 8 *Fasciculithus jani* PERCH-NIELSEN, 1971, sample 36, west El-Hassana section.
- 9 *Fasciculithus pileatus* BUKRY, 1973, sample 242, Gebel Umm Khushayb section.
- 10 *Fasciculithus involutus* BRAMLETTE & SULLIVAN, 1961, sample No.40, west El-Hassana section.
- 11 *Fasciculithus alanii* PERCH-NIELSEN, 1971, sample 45, west El-Hassana section.
- 12–13 *Sphenolithus primus* PERCH-NIELSEN, 1971, sample 245, Gebel Umm Khushayb section.
- 14 *Toweius eminens* (BRAMLETTE & SULLIVAN, 1961), sample 247, Gebel Umm Khushayb section.
- 15 *Cruciplacolithus primus* PERCH-NIELSEN, 1977, sample No.224, Gebel Umm Khushayb section.
- 16 *Chiasmolithus danicus* (BROTZEN, 1959), sample 7, west El-Hassana section.
- 17 *Cruciplacolithus tenuis* (STRADNER, 1961), sample 10, west El-Hassana section.
- 18 *Chiasmolithus bidens* (BRAMLETTE & SULLIVAN, 1961), sample 248, Gebel Umm Khushayb section.
- 19 *Markalius inversus* (DEFLANDRE in DEFLANDRE & FERT, 1954), sample No.6, west El-Hassana section.
- 20–21 *Ericsonia subpertusa* HAY & MOHLER, 1967, sample No.20, west El-Hassana section.
- 22 *Heliolithus kleinpellii* SULLIVAN, 1964, sample No.42, west El-Hassana section.
- 23 *Discoaster mohleri* BUKRY & PERCIVAL, 1971, sample No. 45, west El-Hassana section.

Zone NP4 (absence of Subzone NTp5B and NTp5C and most probably the lowermost of Zone NTp6 of VAROL, 1989). Also a minor hiatus is detected at the NP3/NP4 zonal boundary of the northern scarp of the Farafra Oasis (TAN-

TAWY et al., 2003). The NTp6 Subzone is defined as the interval from the FO of *Ellipsolithus macellus* to the LO of *Neochiastozygus imbrii* HAQ & LOHMANN and *N. eosaepe* PERCH-NIELSEN.



10 um

The distribution of *Ellipsolithus macellus* is considered as being controlled by preservation (dissolution) (MON-ECHI et al., 1985) or different palaeoecological conditions (BACKMAN, 1986, MONECHI et al., 1985).

In the study sections, *E. macellus*, shows a rare and sporadic presence throughout the study interval which may be a result of dissolution and /or the effect of diagenesis.

The subzone NTp7 defines the stratigraphic interval from the LOs of *Neochiastozygus imbrii* and *N. eosaepe* to the FCO (First Common Occurrence) of *Sphenolithus primus*. The FO of *Chiasmolithus edentulus* marks the base of Subzone NTp7B of VAROL (1989) and occurs within Zone NTp7 in the west El-Hassana and Umm Khushayb sections. According to VAROL (1989), the FO of this taxon can be used to directly correlate Tethys and the type area across the D/S boundary. The first occurrence of *Ch. edentulus* in the study sections is easily correlated with the type area of the Danian/Selandian boundary.

The NTp8 has been defined to include the interval from the FO of *Sphenolithus primus* to the FO of *Fasciculithus tympaniformis*. Previous studies have indicated that the occurrences of *Sphenolithus* and *Fasciculithus* (Palaeocene taxa) are closely related. It is generally believed that the genus *Sphenolithus* appears just below the genus *Fasciculithus* (e.g. ROMEIN, 1979; BACKMAN, 1986; BERGGREN et al., 1995), although other authors observed a reverse setting in the relative stratigraphic position of the two biohorizons (VAROL, 1989; BERGGREN et al., 2000).

The onset of the first radiation of *Fasciculithus* species occurs in samples 24 and 240 in the west El-Hassana and Umm Khushayb sections, respectively. The onset of the second radiation of *Fasciculithus* taxa occurs in samples 36 in the west El-Hassana section and in sample 242 in the Umm Khushayb section. Radiation of *Fasciculithus* (*F. pileatus*, *F. bitectus*, *F. involutus*, *F. janii*, and *F. ulii*) first occurred in higher levels above the FO of *S. primus* in the study area.

As proposed by PERCH-NIELSEN (1985b) the FO of *Neochiastozygus perfectus* PERCH-NIELSEN was used for delineating the base of Zone NP5 in North Sea area. In the Zumaia section, the FO of this taxon occurs above the First Common Occurrence (FCO) of *S. primus* and immediately below the LCO of *Braarudosphaera* (DINARES-TURELL et al., 2007). In the two studied sections, *N. perfectus* first appears within Zone NP4 (Zone NTp7).

The FO of *N. perfectus* in Zone NP4 in the study sections is considered to be earlier than reported in the North Sea area, and it is therefore apparently a diachronous event and must be used with caution for long distance correlation.

4.1.4. *Fasciculithus tympaniformis* Zone (NP5)

Definition: The first occurrence (FO) of *Fasciculithus tympaniformis* is used to define the base of Zone NP5 and the FO of *Heliolithus kleinpellii* SULLIVAN defines its top.

Occurrence: This zone occupied the interval from the upper part of the Dakhla and Bedia formations, samples 245–249 (3 m thick) in the Umm Khushayb section, and samples 40–41 in the west El-Hassana section (1.5 m thick).

Characteristic species: The most characteristic species of this zone include those of Zone NP4 in addition to *Fasciculithus tympaniformis*.

Remarks: According to PERCH-NIELSEN (1985b), *Toweius eminens* (BRAMLETTE & SULLIVAN) first appears within Zone NP5. In the Zumaia section, the lowest occurrence of *Toweius eminens* occurs in the middle part of NP5 (DINARÈS-TURELL et al., 2007). At Umm Khushayb, this species (*Toweius eminens*) first occurs within NP5, while in the west El-Hassana section, *T. eminens* is first recorded within the upper part of Zone NP4.

In the study sections, Zone NP5 corresponds to NP5 Zone of MARTINI (1971), the *Fasciculithus tympaniformis*

Plate 3

- 1 *Heterohelix globulosa* (EHRENBERG, 1840), sample 3, west El-Hassana section.
- 2 *Heterohelix navarroensis* LOEBLICH, 1951, sample 6, west El-Hassana section.
- 3 *Heterohelix labellosa* NEDERBAGT, 1991, sample 220, Umm Khyushab section.
- 4 *Pseudoguembelina costulata* (CUSHMAN, 1938), sample 221, Umm Khyushab section.
- 5–6 *Globanomalina compressa* (PLUMMER, 1926), sample 229, Umm Khyushab section.
- 7 *Globanomalina pseudomenardii* (BOLLI, 1957), sample 247, Umm Khyushab section.
- 8–10 *Praemurica inconstans* (SUBBOTINA, 1953), sample 25, west El-Hassana section.
- 11–13 *Morozovella trinidadensis* (BOLLI, 1957), sample 25, west El-Hassana section.
- 14–15 *Igorina albeari* (CUSHMAN & BERMUDEZ, 1949), sample 36, west El-Hassana section.
- 16–18 *Morozovella angulata* (WHITE, 1928), sample 34, west El-Hassana section.
- 19 *Morozovella conicotruncata* (SUBBOTINA, 1947), sample 240, Umm Khyushab section.
- 20–21 *Morozovella oclusa* (LOEBLICH & TAPPAN, 1957), sample 240, Umm Khyushab section.
- 22 *Morozovella pasionensis* (BERMÚDEZ, 1961), sample 34, west El-Hassana section.
- 23 *Acarinina strabocella* (LOEBLICH & TAPPAN, 1957), sample 34, west El-Hassana section.
- 24–25 *Parasubbotina pseudobulloides* (PLUMMER, 1926), sample 224, Umm Khyushab section.
- 26–27 *Parasubbotina varianta* (SUBBOTINA, 1953), sample 246, Umm Khyushab section.
- 28 *Subbotina triangularis* (WHITE, 1928), sample 34, west El-Hassana section.
- 29 *Subbotina trilocolinoides* (PLUMMER, 1926), sample 25, west El-Hassana section.
- 30 *Subbotina velascoensis* (CUSHMAN, 1925), sample 252, Umm Khyushab section. scale bar=100 µm in all figures.

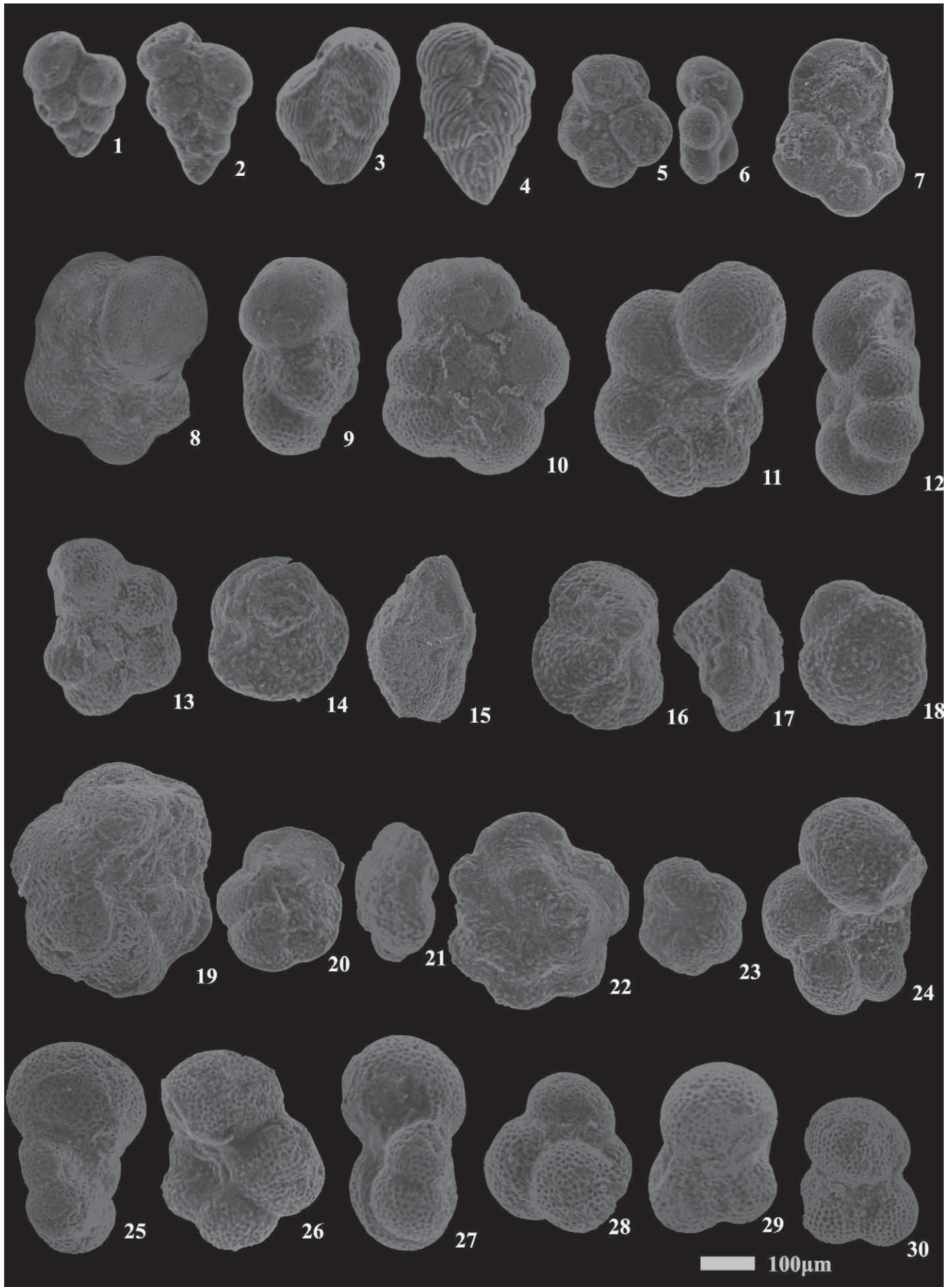


Table 2: continue

| Incoming Paleocene Taxa | | | | | | | | | | | | | | | |
|-------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--------------------------------|
| VR | F | F | R | F | R | R | R | R | R | R | R | R | R | R | Neochiastozygus perfectus |
| R | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Cruciaplacolithus tenuis* |
| VR | F | R | R | R | R | R | R | R | R | R | R | R | R | R | Chiasmolithus danicus* |
| VR | F | R | R | R | R | R | R | R | R | R | R | R | R | R | Cruciaplacolithus primus |
| R | F | R | R | R | R | R | R | R | R | R | R | R | R | R | Coccolithus pelagicus |
| R | F | R | R | R | R | R | R | R | R | R | R | R | R | R | Ericsonia subpertusa |
| R | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Cruciaplacolithus edwardsii |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Neochiastozygus modestus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Neochiastozygus imbricatus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Neochiastozygus eosaepeus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Ellipsolithus macellus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Sphenolithus primus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Chiasmolithus edentulus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus birectus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus pileatus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Ericsonia universa |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Neochiastozygus junctus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus pileatus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Ericsonia universa |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus bobii |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus tympaniformis* |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Chiasmolithus consuetus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Chiasmolithus bidens |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Toweius emimens |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Helolithus cantabriae |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Bomolithus conicus |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Helolithus kleinpellii |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Fasciculolithus alanii |
| | R | R | R | R | R | R | R | R | R | R | R | R | R | R | Discoaster bramlettei |

Abundance
A: Abundant
C: Common
F: Frequent
R: Rare
VR: Very rare

Preservation
G: Good
M: Moderate
P: Poor

* Marker species

zone of ROMEIN (1979), and the CP4 Zone of OKADA & BUKRY (1980), FARIS & ABU SHAMA (2007) and FARIS & SALEM (2007).

4.1.5. *Heliolithus kleinpellii* Zone (NP6)

Definition: The FO of *Heliolithus kleinpellii* defines the base of Zone NP6 and the FO of *Discoaster mohleri* BUKRY & PERCIVAL defines its top.

Occurrence: Zone NP6 occupies the interval from the upper part of the Dakhla and Bedia formations and is represented by samples 250–251 (2.5 m thick) in the Umm Khushayb section and occurs only in sample 42 (0.4 m thick) in the west El-Hassana section.

Characteristic species: In addition to the floral assemblage, which characterizes Zone NP5, the following species are recorded in this zone: *Heliolithus kleinpellii*, *Fasciculithus alanii* PERCH-NIELSEN, *Discoaster bramlettei* MARTINI, and *Bomolithus conicus* (PERCH-NIELSEN).

Remarks: The FO of *Heliolithus cantabriae* PERCH-NIELSEN predates the FO of *H. kleinpellii* in the Umm Khushayb and west El-Hassana sections, and occurs at the top of Zone NP5, in agreement with the observations of PERCH-NIELSEN (1985b) and TANTAWY et al. (2003). In the Umm Khushayb section, *Discoaster bramlettei* occurs at the base of Zone NP6 and is considered here to be a reliable marker for the base of Zone NP6 in this section.

4.1.6. *Discoaster mohleri* Zone (NP7/8)

Definition: The FO of *Discoaster mohleri* BUKRY & PERCIVAL is used to define the base of Zone NP7/8 and the appearance of *Discoaster multiradiatus* BRAMLETTE & REIDEL delineates its top.

Occurrence: This zone is only represented by the Tarawan Formation in the west El-Hassana section (samples 43–45, 1m thick).

Characteristic species: In addition to the identified nanofossils that have been recorded in the Zone NP6; *Discoaster mohleri*, *Fasciculithus schaubii* HAY & MOHLER, and *F. richardii* PERCH-NIELSEN have their first appearance in this zone.

Remarks: The zonal scheme of MARTINI (1971) cannot be applied to this interval because the marker species which defines the NP7/NP8 zonal boundary (*Heliolithus riedelii* BRAMLETTE & SULLIVAN) is absent in the west El-Hassana section. The *Discoaster mohleri* Zone of ROMEIN (1979) is used here. In the Umm Khushayb section, the FO of *Fasciculithus alanii* PERCH-NIELSEN occurs at the base of Zone NP6, while this species first appears at the base of Zone NP7/8 in the west El-Hassana section.

The recorded Zone NP7/8 is equivalent to the combined NP7 and NP8 Zones of MARTINI (1971), the combined CP6 and CP7 Zones of OKADA & BUKRY (1980), and to the NP7/8 Zone of FARIS & ABU SHAMA (2007) and FARIS & SALEM (2007).

4.2. Planktonic foraminifera

4.2.1. *Pseudoguembelina palpebra* partial range Zone (CF2)

Definition: This zone is defined as the biostratigraphic interval from the last occurrence (LO) of *Gansserina gansseri* (BOLLI) to the first occurrence (FO) of *Plummerita hantkeninoides* (BRÖNNIMANN).

Occurrence: This zone occupies the upper part of the Sudr Formation in the study area. Its true thickness is not defined because the base of the Sudr Formation is unexposed in the two studied sections.

Characteristic species. The most dominant planktonic species recorded in this zone yields a relative high abundance of biserial heterohelicids, while pseudoguembelinids, triserial and globotruncanid species are generally very rare (Tables 3 & 4).

Remarks: The *Micula prinsii* Subzone coincides with part of the *Pseudoguembelina palpebra* and the whole *Plummerita hantkeninoides* zones (TANTAWY & KELLER, 2000; KELLER et al., 2007; FAROUK & FARIS, 2008). The absence of *Plummerita hantkeninoides* and *Gansserina gansseri* zones; in addition to the recognition of *Micula prinsii* confirms the presence of the CF2 in the upper part of the Sudr Formation (Fig. 3).

4.2.2. *Eoglobigerina edita* Partial-range Zone

Definition: This zone is defined as the biostratigraphic interval between the LO of *Parvularugoglobigerina eugubina* (LUTERBACHER & PREMOLI SILVA) and the FO of *Praemurica uncinata* (BOLLI).

Remarks: BERGGREN & PEARSON (2005) subdivided the *Eoglobigerina edita* (P1) Zone from older to younger into the: 1) *Parasubbotina pseudobulloides* (P1a), 2) *Subbotina triloculinoides* (P1b) and 3) *Globanomalina compressa/Praemurica inconstans* (P1c) subzones. In the present study, the P1b Subzone occurs directly on the Maastrichtian (CF2 Zone) (Fig. 3).

Subbotina triloculinoides Lowest-occurrence Subzone (P1b)

Definition: This subzone represents the biostratigraphic interval from the FO of *Subbotina triloculinoides* (PLUMMER) to the FO of *Globanomalina compressa* (PLUMMER) and/or *Praemurica inconstans* (SUBBOTINA).

Occurrence: The zone is recorded from the basal part of the Beida Formation and only from the Gebel Umm Khushayb section. It is represented by samples 222–224 (0.5 m thick). This subzone is missing in the west El-Hassana section due to the larger amplitude of the unconformity in this section.

Characteristic species. Characteristic taxa are frequent, moderately well preserved and include *Globoconusa daubjergensis* (BRÖNNIMANN), *Globanomalina archeocompressa* (BLOW), *Parasubbotina pseudobulloides* (PLUM-

MER), *Parasubbotina trivalis* (SUBBOTINA), *Subbotina triloculinoides*, *Praemurica pseudoinconstans* (BLOW), *Chiloguembelina midwayensis* (CUSHMAN) and *Ch. morsei* (KLINE) (Tables 3 & 4).

Remarks: At the K/Pg boundary, several changes are observed in the planktonic foraminiferal assemblages, including the extinction of virtually all Cretaceous species (tropical-subtropical and cosmopolitan), and the first appearance of the Danian species. The Cretaceous species present at the base of a transgression of lower Danian sediments are reworked, and are represented by small cosmopolitan surface water dwellers such as *Heterohelix* and *Pseudoguembelina* with very rare *Rugoglobigerina* and *Globotruncana* spp..

The FOs of *Globanomalina compressa* and/or *Praemurica inconstans* have been used to determine the base of Subzone P1c (OLSSON et al., 1999; BERGGREN & PEARSON, 2005). The authors believe that the FO of *Globanomalina compressa* predates that of the FO of *Praemurica inconstans*, and occurs within Zone P1b. A similar occurrence in Subzone P1b was also reported by KELLER (2002). According to BERGGREN & PEARSON (2005), Zone P1b falls between the top part of the *Cruciplacolithus tenuis* (NP2) Zone, and the basal part of the *Chiasmolithus danicus* (NP3) Zone. Therefore, the authors believe that the base of Zone P1b

should be absent in the Gebel Umm Khushayb due to absences of the *Cruciplacolithus tenuis* Zone NP2.

***Globanomalina compressa*/*Praemurica inconstans* Lowest-occurrence Subzone (P1c)**

Definition: The biostratigraphic interval from the FO of *Globanomalina compressa* and/or *Praemurica inconstans* and the FO of *Praemurica uncinata*.

Occurrence: This zone is recorded from the lower part of the Dakhla Formation and represented only by samples 7–8 (2.0 m thick) from the west El-Hassana section and it encompasses, samples 224–230 (3.0 m thick) at the Gebel Umm Khushayb section.

Characteristic species. In this interval the species are highly abundant and well preserved. The assemblage of this interval is similar to that of the underlying Subzone P1c with the addition of four more species *Praemurica inconstans*, *Globanomalina compressa* and *Parasubbotina varianta* (SUBBOTINA), *Morozovella trinidadensis* (BOLLI).

Remarks: KELLER (2002) subdivided Subzone P1c into two subzones, P1c (1) and P1c (2) based on the first appearance of *Praemurica inconstans*. In the present study, the FOs of *Praemurica inconstans*, *Globanomalina compressa*

| Age | Planktonic foraminifera | | | | Calcareous nannofossils | | | |
|---------------------------------|--|---|--|------------------------------|------------------------------------|-------------------|---|--------------------------|
| | BERGGREN & PEARSON (2005) and LI & KELLER (1998) | This study | | | MARTINI (1971) and SISSINGH (1977) | VAROL (1989) | | |
| | | Planktonic foraminiferal datum events | Plank. foram. zones | Calcareous nannofossil zones | | | | Nannofossil datum events |
| PALEOCENE | Thanetian | <i>Ac. subsphaerica</i> (P4b) | P4 | P4b | NP7/8 | <i>D. mohleri</i> | NTp16A | |
| | | | | | | | NTp15 | |
| | Selandian | <i>Gl. pseudomenardii</i> / <i>P. variospira</i> (P4a) | <i>P. variospira</i> | P4 | P4a | NP6 | <i>H. kleinpellii</i> | NTp11 |
| | | | | | | | | NTp10 |
| | | <i>I. albeari</i> (P3b) | <i>M. velascoensis</i> <i>M. velascoensis</i> | P3 | P3b | NP5 | <i>F. tympaniformis</i> | NTp9 |
| | | | | | | | | NTp8 |
| | | | | | | | | NTp7 |
| | Danian | <i>I. pusilla</i> (P3a) | <i>I. albeari</i> <i>I. pusille</i> <i>M. angulata</i> | P3 | P3a | NP4 | (FCO) of <i>S. primus</i> | NTp8 |
| | | | | | | | | NTp7 |
| | Danian | <i>P. uncinata</i> (P2) | <i>Pr. uncinata</i> | P2 | P2 | NP4 | <i>N. imbrii</i> & <i>N. eosaepe</i> | NTp7 |
| | | | | | | | | NTp6 |
| | | <i>Gl. compressa</i> / <i>P. inconstans</i> (P1c) | <i>P. inconstans</i> | P1 | P1c | NP3 | <i>E. macellus</i> | NTp6 |
| | | | | | | | | NTp5 |
| <i>S. triloculinoides</i> (P1b) | | <i>S. triloculinoides</i> & <i>G. compressa</i> | P1 | P1b | NP3 | <i>C. danicus</i> | NTp4 | |
| | | | | | | | NTp3 | |
| | | | | | | | NTp2 | |
| Danian | <i>P. pseudobulloides</i> (P1a) | Hiatus | Hiatus | Hiatus | Hiatus | Hiatus | NTp3 | |
| | | | | | | | NTp2 | |
| Danian | P0 & Pα | Hiatus | Hiatus | Hiatus | Hiatus | Hiatus | NTp1 | |
| | | | | | | | NTp1 | |
| | | | | | | | NTp1 | |
| Maas. | <i>P. hantkeninoides</i> (CF1) | <i>P. hantkeninoides</i> | CF2 | CF2 | <i>M. prinsii</i> | <i>M. prinsii</i> | NTp1 | |
| | | | | | | | NTp1 | |
| Maas. | <i>P. palpebra</i> (CF2) | <i>P. hantkeninoides</i> | CF2 | CF2 | <i>M. prinsii</i> | <i>M. prinsii</i> | Not zoned | |
| | | | | | | | Not zoned | |

Figure 3: Standard and alternative planktonic foraminiferal and calcareous nannofossil biozonations for the Palaeocene interval.

Table 3: Stratigraphic distribution of planktonic foraminiferal taxa identified in the west El-Hassana section.

| Latest Maes. Sudr | D a n i a n | | Selandian | | | | | | | | Thanetian Tarawan | | Age Formation | Planktonic foramin. Zone | |
|-------------------|-------------|-----|-----------|-----|-----|-----|-----|-----|--|--|-------------------|-----|---------------|--------------------------|--|
| | M. prinsii | CF2 | NP4 | | | | P3 | | | | NP6 | P4b | Sample No. | | |
| | | | NP7 | NP8 | P3a | P3b | P3c | P4a | | | | | | | |
| 6 | | | | | | | | | | | | | | | <i>Globotruncana aegyptiaca</i> |
| 5 | | | | | | | | | | | | | | | <i>Globotruncana rosetta</i> |
| 4 | | | | | | | | | | | | | | | <i>Rugoglobigerina hexacamerata</i> |
| 3 | | | | | | | | | | | | | | | <i>Rugoglobigerina macrocephala</i> |
| 2 | | | | | | | | | | | | | | | <i>Rugoglobigerina rugosa</i> |
| 1 | | | | | | | | | | | | | | | <i>Heterohelix globulosa</i> |
| | | | | | | | | | | | | | | | <i>Heterohelix dentata</i> |
| | | | | | | | | | | | | | | | <i>Heterohelix navarroensis</i> |
| | | | | | | | | | | | | | | | <i>Heterohelix striata</i> |
| | | | | | | | | | | | | | | | <i>Pseudoguembelina hariaensis</i> |
| | | | | | | | | | | | | | | | <i>Pseudoguembelina costulata</i> |
| | | | | | | | | | | | | | | | <i>Pseudotextularia elegans</i> |
| | | | | | | | | | | | | | | | <i>Globotruncanella subcarinatus</i> |
| | | | | | | | | | | | | | | | <i>Subbotina triloculinoises*</i> |
| | | | | | | | | | | | | | | | <i>Subbotina trivialis</i> |
| | | | | | | | | | | | | | | | <i>Subbotina triangularis</i> |
| | | | | | | | | | | | | | | | <i>Subbotina cancellata</i> |
| | | | | | | | | | | | | | | | <i>Subbotina velascoensis</i> |
| | | | | | | | | | | | | | | | <i>Parasubbotina pseudobulluloides</i> |
| | | | | | | | | | | | | | | | <i>Parasubbotina varianta</i> |
| | | | | | | | | | | | | | | | <i>Parasubbotina variospira</i> |
| | | | | | | | | | | | | | | | <i>Praemurica inconstans*</i> |
| | | | | | | | | | | | | | | | <i>Praemurica uncinata*</i> |
| | | | | | | | | | | | | | | | <i>Globanomalina compressa</i> |
| | | | | | | | | | | | | | | | <i>Globanomalina ehrenbergi</i> |
| | | | | | | | | | | | | | | | <i>Globanomalina pseudomenardii*</i> |
| | | | | | | | | | | | | | | | <i>Chiloguembelina midwayensis</i> |
| | | | | | | | | | | | | | | | <i>Chiloguembelina morsei</i> |
| | | | | | | | | | | | | | | | <i>Igorina pusilla</i> |
| | | | | | | | | | | | | | | | <i>Igorina albeari*</i> |
| | | | | | | | | | | | | | | | <i>Morozovella praesagulata</i> |
| | | | | | | | | | | | | | | | <i>Morozovella angulata*</i> |
| | | | | | | | | | | | | | | | <i>Morozovella conicotruncata</i> |
| | | | | | | | | | | | | | | | <i>Morozovella apantesma</i> |
| | | | | | | | | | | | | | | | <i>Morozovella pasionensis</i> |
| | | | | | | | | | | | | | | | <i>Morozovella velascoensis*</i> |
| | | | | | | | | | | | | | | | <i>Morozovella acuta</i> |
| | | | | | | | | | | | | | | | <i>Morozovella preaequa</i> |
| | | | | | | | | | | | | | | | <i>Morozovella aequa</i> |
| | | | | | | | | | | | | | | | <i>Morozovella occlusa</i> |
| | | | | | | | | | | | | | | | <i>Acarinina strabocella</i> |
| | | | | | | | | | | | | | | | <i>Acarinina mckennai</i> |

A= Abundant
 C= Common
 F= Frequent
 VR= Very Rare
 R= Rare
 r=reworked
 *marker species

pressa, *Parasubbotina pseudobulloides*, *Parasubbotina varianta*, *Subbotina concellata* (BLOW), *S. trinagularis* (WHITE), *S. triloculinoidea*, *S. trivialis*, *Praemurica uncinata*, *P. inconstans* and *Morozovella praeangulata* (BLOW) (Tables 3 & 4).

Remarks: *Subbotina triangularis* and *S. concellata* first appear within the upper part of this biozone (Tables 3 & 4). STEURBAUT & SZTRÁKOS (2008), mentioned that the *Praemurica uncinata* Zone falls within the top part of the calcareous nannofossil Zone NTP6 in south-west France. In the present study, it falls within Zone NTP6 and the lower part of Zone NTP7. A similar occurrence was also reported by STEURBAUT et al. (2000) in the Kalaat Senan section, central Tunisia.

4.2.4. *Morozovella angulata*-*Globanomalina pseudomenardii* Interval Zone (P3)

Definition: This includes the interval from the FO of *Morozovella angulata* to the FO of *Globanomalina pseudomenardii* (BOLLI).

Occurrence: The biozone is represented by samples 30–39 (4.5 m thick) in west El-Hassana, and sample 237–243 (7 m thick) from Gebel Umm Khushayb. Various authors have observed that Zone P3 is condensed in this area (e.g. SAMIR, 2002; AL-WOSABI & ABU SHAMA, 2007 in Egypt; VAN ITTERBEEK et al., 2007 in Tunisia).

Remarks: BERGGREN et al. (1995), BERGGREN & NORRIS (1997) and OLSSON et al. (1999) re-subdivided P3 Zone into two subzones: the *Morozovella angulata*-*Igorina albeari* Interval Subzone (P3a) and the *Igorina albeari*-*Globanomalina pseudomenardii* Interval Subzone (P3b). In the present study the P3 Zone can also be divided into two subzones.

Morozovella angulata-*Igorina albeari* Interval Subzone (P3a)

Definition: interval from the FO of the *Morozovella angulata* to the FO of *Igorina albeari* (CUSHMAN & BERMUDEZ).

Characteristic species. The planktonic assemblage of this subzone is dominated by morozovellids with angular conical chambers throughout their youngest whorl, such as *Morozovella conicotruncata* (Subbotina), *M. Praeangulata*, *M. angulata* (WHITE), and *M. praecursoria* (MOROZOVA). In addition, other taxa are also present: *Subbotina triloculinoidea*, *Globanomalina compressa*, *Igorina pusilla* and *Praemurica uncinata* (Tables 3 & 4).

Remarks: *Globanomalina compressa*, *Praemurica uncinata*, and *P. inconstans* disappeared in the lower part of this subzone.

Igorina albeari/*Globanomalina pseudomenardii* Interval Subzone (P3b)

Definition: This represents the Interval between the FO of *Igorina albeari* and the FO of *Globanomalina pseudomenardii* (BOLLI).

Characteristic species. *Morozovella angulata*, *M. conicotruncata*, *Parasubbotina varianta*, *M. velascoensis* (CUSHMAN), *M. occlusa* (LOEBLICH & TAPPAN), *M. acuta* (TOULMIN), *M. aequa* (CUSHMAN & RENZ), *Subbotina velascoensis* (CUSHMAN), *Subbotina triloculinoidea Igorina albeari* and *I. pusilla* (BOLLI) are the dominant planktonic species in the P3 b Subzone.

Remarks. *Morozovella conicotruncata* and *M. passionensis* first appeared within the lower part of this subzone, while *M. velascoensis*, *M. occlusa*, *M. acuta*, *M. praeaequa* and *Subbotina velascoensis* first occurred within the upper part of the subzone (Tables 3 & 4).

4.2.5. *Globanomalina pseudomenardii* Total Range Zone (P4)

Definition: This zone is defined as the interval of the total range of the nominated taxon.

Occurrence: The zone occupies about 5.5 m of the uppermost part of the measured Beida Formation at Gebel Umm Khushayb and is represented by samples 244–251. It also occurs in the topmost part of the Dakhla Formation, as well as the whole Tarawan Formation at the west El-Hassana section (samples 40–45).

Characteristic species. The dominant species in this subzone include angular morozovellids such as *Morozovella acuta*, *M. aequa*, *M. velascoensis*, *M. occlusa*, *Acarinina mckannai* (WHITE), *A. strabocella* (LOEBLICH & TAPPAN) and *Subbotina velascoensis*.

Remarks. BERGGREN AND PEARSON (2005) subdivided the P4 Zone into three subzones; *Globanomalina pseudomenardii*/*Parasubbotina variospira* (P4a) concurrent-range Subzone; *Acarinina subsphaerica* (P4b) Partial-range Subzone and *Acarinina soldadoensis*/*Globanomalina pseudomenardii* (P4c) concurrent-range Subzone. In the current study, it was also difficult to subdivide the P4 into these biozones due to the poor preservation of foraminiferal tests as a result of carbonate dissolution.

OLSSON et al. (1999) reported that the FO of *Morozovella aequa* occurs at the lower boundary of the P4c Zone. In the present study, the FO of *Morozovella aequa* is recognized at the top part of P3b Zone, which is equivalent to the top part of the calcareous nannofossil NP4 Zone. A similar occurrence in the P3b Zone was also reported by ARENILAS (2012) in the Caravaca section of Spain.

5. STAGE BOUNDARIES

5.1. The Cretaceous/Palaeogene (K/Pg) boundary

The K/Pg boundary is marked by an abrupt lithological change that corresponds to the boundary between the Sudr and Dakhla formations at the west El-Hassana section or to the Sudr / Beida formation at Umm Khushayb. Biostratigraphic analysis (planktonic foraminifera, calcareous nannofossils) confirms that the studied sections are incomplete and discontinuous across the K/P boundary. A small hiatus is suggested by the absence of the *Plummerita hantkeni*

noides, *Guembelitra cretacea*, *Parvularugoglobigerina eugubina* Zones and *Parasubbotina pseudobulloides* Subzone. In the west El-Hassana section, the *Subbotina triloculinoidea* Subzone is also missing. Moreover, the upper part of the calcareous nannofossil *Micula prinsii* Subzone and the earliest Danian Zones (NP1 and NP2) are missing. This hiatus may be linked to tectonic activity and irregular palaeotopography associated with low sedimentation rates as suggested by FAROUK & FARIS (2008).

The K/Pg boundary is characterized by the extinction of Cretaceous tropical planktonic foraminifera, and an abrupt change in species richness. However, most of the Cretaceous calcareous nannofossil vanishing species progressively decrease in abundance within Zone NP4; only the most dissolution-resistant Cretaceous species (*Micula decussata*, *Watznaueria barnesae*) are still present near the top of Zone NP4. The Cretaceous persistent species progressively increase in abundance above the K/Pg boundary. *Cyclagelosphaera reinhardtii* is the most common Cretaceous persistent species in the Palaeocene.

5.2. The Danian/Selandian boundary

The global stratotype section and point (GSSP) across the Danian/Selandian (Da/Se) boundary has been defined in the Zumaia section, northern Spain close to the FO of *F. tympaniformis*, just below the NP4/NP5 boundary and within the planktonic foraminiferal P3b Zone (BERNOALA et al., 2009). Based on calcareous nannofossils, the Danian/Selandian (Da/Se) boundary is delineated at a level close to the FO of *Fasciculithus tympaniformis*, just below the NP4/NP5 boundary and it coincides with the End Acme of *Braarudosphaera bigelowii* (BERNOALA et al., 2009). The Lowest Common Occurrence (LCO) of *Braarudosphaera*, which marked the lithological change at the D/S boundary at the type area in Denmark, can be directly correlated with the abrupt transition from the Danian limestones to the marly Itzurun Fm. at Zumaia (SCHMITZ et al., 1998; BERNAOLA et al., 2009). This event is not applicable to the Tethyan sections because *Braarudosphaera* was not recorded there (BERNAOLA et al., 2009). The Last Common Occurrence (LCO) of *Braarudosphaera* seems applicable for placing the base of the Selandian in Denmark, but it is an unreliable event for delineating the Danian/Selandian boundary in the study sections.

Previously in Egypt, the Danian/Selandian was marked as a prominent organic-rich layer with a short-term sea-level fall coinciding with the P3a/P3b boundary, by using the lowest occurrence of the slightly keeled *Igorina* as a zonal boundary criterion (SPEIJER, 2003; OBAIDALLA et al., 2009; SPRONG et al., 2009). In the Qreiya section, the organic-rich layer occurs approximately 1 m above the FOs of *Chiasmolithus edentulus* and small fasciculiths (SPRONG et al., 2009). This event bed at the D/S boundary, situated at the base of the Subzone NTp7B, and the equivalent planktonic foraminiferal P3a/P3b zonal boundary, is now considered latest Danian in age (BERNOALA et al., 2009; YOUSSEF, 2009).

On the other hand, FARIS & ABU SHAMA (2007) put the Danian/Selandian boundary at the base of Zone NP5. In the present study, it is bracketed within the Zone NTp8 (topmost NP4 equivalent to top part of the planktonic foraminifera P3b Subzone), at a level close to the First Occurrence (FO) of *Morozovella velascoensis*, *M. occulsa*, *M. aquea* and *M. acuta* (below) and the FO of *Fasciculithus tympaniformis* (above) just below the NP4/NP5 boundary in west El-Hassana and Umm Khushayb sections, is similar to that of the Global Standard Stratotype-section and Point (GSSP) of the Da/Se boundary which has recently been selected at the Zumaia section.

An important global nannofossil event is the onset of the second radiation of *Fasciculithus* (*F. bitectus*, *F. involutus*, *F. jani*, *F. billii* and *F. ulii*). It starts within Zone NTp8 (topmost NP4 and P3b) at a level close to the FO of *F. tympaniformis* and just below the NP4/NP5 boundary in the study sections.

The first continuous occurrence (FCO) of *Sphenolithus primus*, the marker taxon for the base of Subzone NTp8A of VAROL (1989), is a reliable marker for delineating the Danian/Selandian transition (FARIS et al., 2005, QUILLVERE et al., 2002). In the present study, the FRO (First Rare Occurrence) of *Sphenolithus primus* is not a useful global marker because it occurs rarely and sporadically. STEURBAUT & SZTRÁKOS (2008) and BERNAOLA et al. (2009) also reported a similar occurrence for the FRO of *Sphenolithus primus*.

5.3. The Selandian/Thanetian boundary

The base of the Thanetian in its original type area, has been correlated within the upper part of the nannofossil Zone NP6 (AUBRY, 1994; KNOX, 1994). The base of Chron C26n at Zumaia, as a continuous, deep marine and cyclic sequence, offers the possibility of establishing a potential Thanetian Unit Stratotype (DINARÈS-TURELL et al., 2007). It is positioned 30.5 m above the base of the Itzurun Formation, very close to the base of Chron C26N (SCHMITZ et al., 1998).

A minor hiatus is proposed at the Selandian/Thanetian boundary as indicated by a condensed interval that marks a lithological change from the calcareous shales of the Dakhla Formation to the limestones of the Tarawan Formation. Therefore, the Selandian/Thanetian boundary in the present study is located at the top of Zone NP6 and within the lower part of the *Globanomalina pseudomenardii* Zone. No great changes in the nannofossil assemblages have been observed in the west El Hassana section, except for the FO of *Discoaster mohleri*. The *Heliolithus kleinpellii* Zone (NP6) is not recorded in several localities in Egypt (e.g. BASSIOUNI et al., 1991; FARIS et al., 1999; FARIS & ZAHRAN, 2002; AYYAD et al., 2003).

6. CONCLUSIONS

The results obtained can be summarized as follows:

1. An integrated calcareous nannofossil and planktonic foraminiferal biostratigraphy has been achieved for the

- Upper Maastrichtian-Palaeocene successions on the west El-Hassana and Umm Khushayb sections, north-central Sinai. The Maastrichtian – Palaeocene material studied in this work consists of siliciclastic/carbonate deposits belonging to four formations: The Sudr, Dakhla, Tarawan formations, and their lateral coeval Beida Formation.
- 44 calcareous nannofossil and 31 planktonic foraminiferal taxa are identified with moderate to good preservation and relatively high diversity. These microfossil assemblages allowed subdivision of the study sections into one subzone and five calcareous nannofossil zones: *Micula prinsii* Subzone (CC26c), *Chiasmolithus danicus* Zone (NP3), *Ellipsolithus macellus* Zone (NP4), *Fasciculithus tympaniformis* Zone (NP5), *Helolithus kleinpelli* Zone (NP6), *Discoaster mohleri* Zone (NP7/8); and five planktonic foraminiferal zones and four subzones; *Pseudoguembelina palpebra* Zone (CF2), *Eoglobigerina edita* (P1) Zone, *Praemurica uncinata* Zone (P2), *Morozovella angulata-Globanomalina pseudomenardii* Zone (P3), *Globanomalina pseudomenardii* Zone (P4). Zone P1 can be subdivided into the *Subbotina triloculinoidea* Subzone (P1b), and the *Globanomalina compressa/Praemurica inconstans* Subzone (P1c). Zone P3 is subdivided into the *Morozovella angulata-Igorina albeari* Subzone (P3a), and the *Igorina albeari/Globanomalina pseudomenardii* Subzone (P3b).
 - Biostratigraphic analyses of the two studied sections based on planktonic foraminifera and calcareous nannofossils, indicate that deposition of the Latest Maastrichtian to Early Danian sediments was interrupted by erosion and or non-deposition related to tectonic activity. As a result, some planktonic foraminifera (*Plummerita hantkeninoides*, *Guembelitra cretacea*, *Parvularugoglobigerina eugubina* biozones and, *Parasubbotina pseudobulloidea* Subzone and their equivalent calcareous nannofossils (top part of CC26c, NP1 and NP2 zones) are missing.
 - The new-Palaeocene calcareous nannofossil taxa first appear at the base of Zone NP3 of early Danian age. They progressively increase upwards and are more common than the Cretaceous vanishing species in Zone NP3 and NP4.
 - According to the Palaeocene Zonal Scheme of VAROL (1989); the nannofossil Zone NP4 of MARTINI (1971), can be divided into three subzones; NTp6, NTp7 and NTp8 in the west El-Hassana and Umm Khushayb sections. A small hiatus is observed at the NP3/NP4 zonal boundary as suggested by the absence of the NTp5B Subzone and NTp5C and most probably the lowermost part of Zone NTp6.
 - The onset of a second diversification of the genus *Fasciculithus*, represented by *F. bitectus*, *F. involutus*, *F. jannii*, *F. billii* and *F. ulii*, begins within Zone NTp8 and just below the NP4/NP5 boundary in El Hassana and Umm Khushayb sections. This radiation marks the Danian/Selandian boundary. Based on planktonic forami-

nifera, the Danian/Selandian boundary lies with the basal part of the P3b Subzone.

- The Selandian/Thanetian boundary is placed at the contact between the Dakhla and Tarawan formations at west El-Hassana, approximately at the top of calcareous nannofossil Zone NP6 within the equivalent planktonic foraminiferal Zone P4. A minor hiatus was observed at this boundary as indicated by the prominent lithological change from the calcareous shale of the Dakhla Formation to the limestones of the Tarawan Formation and the very condensed calcareous nannofossil Zone NP6.

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