

Calcareous Nannofossils Biostratigraphy and Paleoecology of the Late Paleocene/Early Eocene of Wadi Nukhul, Westcentral Sinai, Egypt

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Abstract: The calcareous nannofossil biozones NP7/8 through NP12 were identified from the Esna and base of the Thebes formations at Wadi Nukhul, westcentral Sinai. The Subzone NP9a spans the lower part of Esna Formation. The Zone NP10 is easily differentiated into 4 subzones (a-d). The NP9/NP10 zonal boundary can be identified at the level of increase frequency of *Neochiastozygus junctus*. Zone NP11 occupies the topmost part of the Esna Formation and the base of the Thebes Formation indicating conformable relation between them. The Paleocene/Eocene boundary is traced between the NP9a/NP9b subzonal boundary which is marked by the first- appearances of *Rhomboaster* spp. It is located at the basal part of the Esna Formation and conforms lithologic change from blackish calcareous shale to brown calcarenite. On the basis of nannofossils, the Paleocene Eocene Thermal maximum (PETM) interval can be divided into two parts (lower and upper). The major assemblage shift across the P/E boundary suggests a change from colder, more productive surface waters to warmer, more oligotrophic conditions. Above the PETM interval, the niche of *Fasciculithus* spp. was filled by *Neochiastozygus junctus* and *Rhabdolithus solus*, the cooler and more eutrophic taxa.

Keywords: Nannofossils, Paleocene, Eocene, Sinai, Nukhul, Egypt

1. Introduction

The southern Tethyan margin is of particular interest for studying lower Paleogene continental-margin records, as it provides continuously well-exposed outcrops and well-preserved material for micropaleontological research. For these reasons, the Global Standard Stratotype section and Point (GSSP) for the Paleocene/Eocene has been proposed recently in the lowermost part of the Esna Shale at the Dababiya section in central Egypt (Aubry et al., 2002). The Paleocene-Eocene Thermal Maximum (PETM) in Egypt has been intensively investigated mainly on the basis of smaller benthic foraminifera (Speijer, 1994; Speijer et al., 1996a, 1996b, 1997; Youssef, 2004; Alegret et al., 2005; Ernst et al., 2006; Guasti and Speijer 2007), planktic foraminifera (Obaidalla, 2000; Berggren and Ouda, 2003; Ouda et al., 2003; Al Wosabi, 2014), nannoplankton (Aubry et al., 1996; Monechi et al., 2000; Faris et al., 2000; Faris and Zahran, 2002; Tantawy et al., 2001; Youssef, 2004; Abu Shama et al., 2007; Khozyem et al., 2013).

In the central Nile Valley, the Paleocene-Eocene

succession reaches up to 2m thick and attracted the attention of many geologists since many decades. However, in Sinai, the Paleocene-Eocene succession is greatly reduced in thickness.

Wadi Nukhul is located in the eastern side of the Gulf of Suez, about 6 km south of Abu Zenima City, southwestern Sinai (Fig.1).

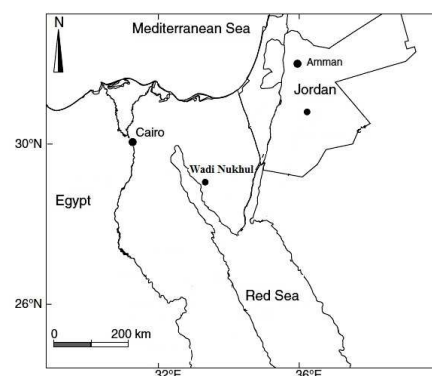


Fig. 1. Location map of the study area.

The main purposes of this work are: 1) to study the calcareous nannofossil biozonation for the Tarawan, Esna and the base of the Thebes formations at Wadi Nukhul. 2) to determine the Paleocene-Eocene boundary based on the calcareous nannofossils taxa and 3) to investigate the calcareous nannofossil events related to paleoecologic conditions at this boundary.

2. Material and Methods

Nannofossils were observed in the light microscope at 1250X magnification and identified following the taxonomic schemes of Perch-Nielsen 1985. For statistical analyses across the Paleocene/Eocene boundary, 50 views of smear slides were counted and analyzed (Table 1).

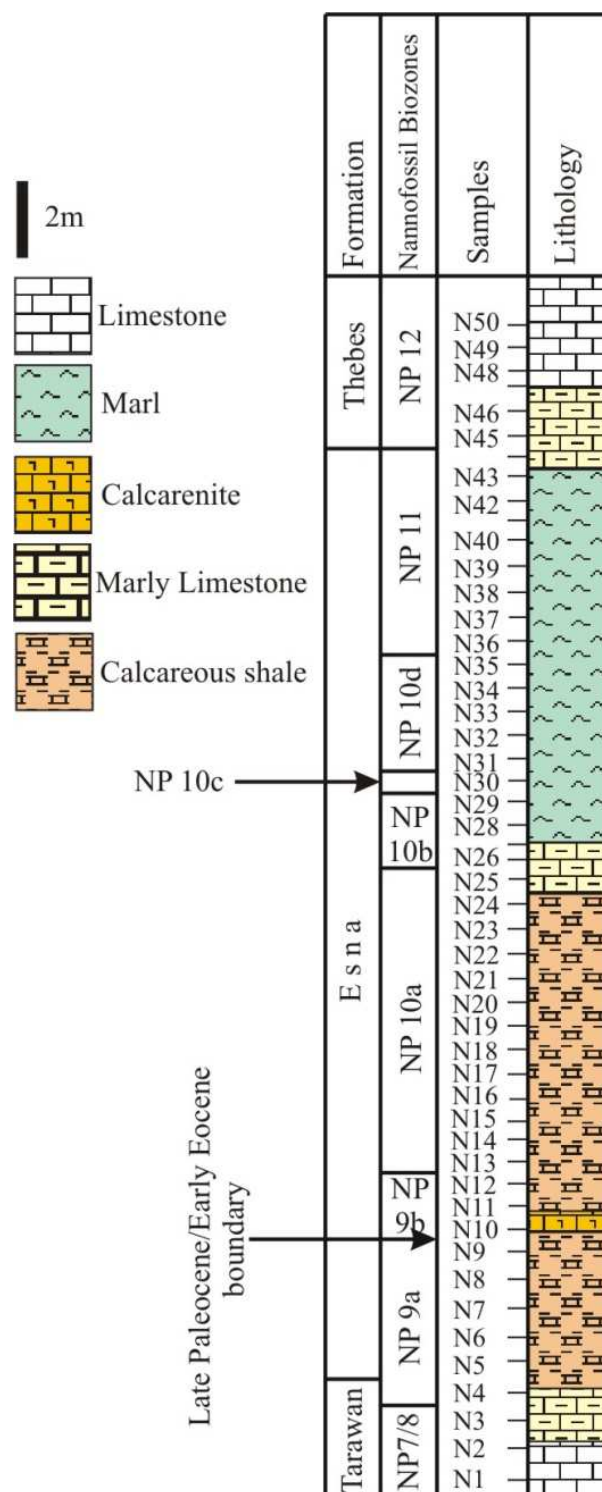


Fig. 2. Lithostratigraphic section of the studied samples at Wadi Nukhul, westcentral Sinai, Egypt.

Table 1. Changes in the Relative abundance of selected calcareous nannofossil assemblage across the Paleocene/Eocene boundary, Wadi Nukhul, westcentral Sinai, Egypt.

| Age | Sample No. | Nannofossil Zones | Formation | <i>Fasciculithus tympaniformis</i> * | <i>Sphenolithus primus</i> * | <i>Ericsonia cava</i> | <i>Ericsonia subpertusa</i> | <i>Obliquipithonella operculata</i> | <i>Bomolithus elegans/ B.conicus</i> | <i>Discoaster mohleri</i> * | <i>Fasciculithus</i> spp. | <i>Chiasmolithus</i> spp. | <i>Discoaster nobilis</i> | <i>Toweius</i> spp. | <i>Discoaster multiradiatus</i> * | <i>Discoaster falcatus</i> | <i>Fasciculithus alanii</i> | <i>Discoaster megastypus</i> | <i>Fasciculithus lilliana</i> | <i>Fasciculithus involutus</i> | <i>Fasciculithus aubertae</i> | <i>Discoaster mahnoudii</i> * | <i>Pontosphaera multipora</i> | <i>Discoaster araneus</i> * | <i>Rhomboaster</i> spp. | <i>Rhomboaster birrifida</i> * | <i>Neochiastozygus juncatus</i> | <i>Discoaster binodosus</i> | <i>Rhabdosphaera solus</i> * | <i>Campylosphaera eodella/dela</i> | <i>Discoaster diastypus</i> * | <i>Tribrachiatius bramlettei</i> | <i>Zygrhablithus bijugatus</i> | Total |
|----------------|------------|-------------------|-----------|--------------------------------------|------------------------------|-----------------------|-----------------------------|-------------------------------------|--------------------------------------|-----------------------------|---------------------------|---------------------------|---------------------------|---------------------|-----------------------------------|----------------------------|-----------------------------|------------------------------|-------------------------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-------------------------|--------------------------------|---------------------------------|-----------------------------|------------------------------|------------------------------------|-------------------------------|----------------------------------|--------------------------------|-------|
| early Eocene | N21 | | D | 3 | 55 | 19 | | | | | 43 | | | 3 | | | | | | | 2 | 3 | | 2 | 6 | 26 | 21 | 53 | 3 | 8 | 8 | 4 | 259 | |
| | | | % | 1 | 21 | 7 | | | | | 17 | | | 1 | | | | | | | 0.7 | 1 | | 0.7 | 2.3 | 10 | 8 | 20.4 | 1 | 3 | 3 | 1.5 | 98.6 | |
| | N20 | | D | 7 | 31 | 21 | | | | | 51 | | | 3 | | | | | | | 3 | 9 | | 2 | 7 | 28 | 9 | 55 | 8 | 7 | 11 | 3 | 255 | |
| | | | % | 2.7 | 12.1 | 8.2 | | | | | 20 | | | 1.1 | | | | | | | 1.1 | 3.5 | | 0.7 | 2.7 | 10.8 | 3.5 | 21.5 | 3.1 | 2.7 | 4.3 | 1.1 | 99.1 | |
| | N19 | | D | 9 | 61 | 51 | | | | | 47 | | | 4 | | | | | | | 2 | 12 | | 3 | 6 | 38 | 2 | 50 | 3 | 4 | 7 | 4 | 303 | |
| | | | % | 3 | 20.1 | 16.8 | | | | | 15.5 | | | 1.3 | | | | | | | 0.7 | 4 | | 1 | 2 | 12.5 | 0.7 | 16.5 | 1 | 1.3 | 2.3 | 1.3 | 100 | |
| | N18 | | D | 8 | 60 | 44 | | | | | 54 | | | 3 | | | | | | | 3 | 11 | | 3 | 3 | 25 | 4 | 69 | 4 | 3 | 4 | | 298 | |
| | | | % | 2.7 | 20.1 | 14.8 | | | | | 18.1 | | | 1 | | | | | | | 1 | 3.7 | | 1 | 1 | 8.4 | 1.3 | 23.2 | 1.3 | 1 | 1.3 | | 100 | |
| | N17 | NP10a | D | 7 | 45 | 42 | 2 | | | | 51 | | | 7 | | | | | | | 33 | 25 | | 3 | | 31 | 3 | 60 | | 3 | 3 | | 315 | |
| | | | % | 2.2 | 14.2 | 13.3 | 0.6 | | | | 16.5 | | | 2.2 | | | | | | | 10.4 | 7.9 | | 0.9 | | 9.8 | 0.9 | 19 | | 0.9 | 0.9 | | 100 | |
| | N16 | | D | 4 | 30 | 25 | 3 | | | | 32 | | | 22 | | | | | | | 4 | 18 | | 4 | 4 | 30 | 3 | 67 | | 8 | 4 | | 258 | |
| | | | % | 1.6 | 11.6 | 9.7 | 1.2 | | | | 12.4 | | | 8.5 | | | | | | | 1.6 | 7 | | 1.6 | 1.6 | 11.6 | 1.2 | 26 | | 3.1 | 1.6 | | 100 | |
| | N15 | | D | 3 | 28 | 16 | 4 | | | | 38 | | | 12 | 2 | | | | | | 2 | 8 | | 4 | 3 | 27 | 3 | 53 | | 4 | 2 | | 209 | |
| | | | % | 1.4 | 13.4 | 7.7 | 1.9 | | | | 18.2 | | | 5.7 | 1 | | | | | | 1 | 3.8 | | 1.9 | 1.4 | 12.9 | 1.4 | 25.4 | | 1.9 | 1 | | 100 | |
| | N14 | | D | 4 | 50 | 42 | 3 | | | | 30 | | | 20 | 3 | | | | | | 3 | 6 | | 3 | | 23 | 2 | 50 | | 3 | 2 | | 244 | |
| | | | % | 1.6 | 20.5 | 17.2 | 1.2 | | | | 12.3 | | | 8.2 | 1.2 | | | | | | 1.2 | 2.5 | | 1.2 | | 9.4 | 0.8 | 20.5 | | 1.2 | 0.8 | | 99.8 | |
| | N13 | | D | 1 | 8 | 58 | 49 | | | | 43 | | | 17 | 2 | | | | | 3 | | 2 | 3 | 5 | 3 | 1 | 29 | 1 | 33 | | 2 | 1 | | 261 |
| | | | % | 0.4 | 3.1 | 22.2 | 18.8 | | | | 16.5 | | | 6.5 | 0.8 | | | | 1.1 | | 0.8 | 1.1 | 1.9 | 1.1 | 0.4 | 11.1 | 0.4 | 12.6 | | 0.8 | 0.4 | | 100 | |
| | NP9b | Esna | N12 | D | 1 | 8 | 27 | 23 | | | | 29 | | | 17 | 6 | | 3 | | 3 | 1 | 3 | 4 | 6 | 3 | 5 | 23 | 4 | 18 | 3 | | | | 187 |
| | | | | % | 0.5 | 4.3 | 14.4 | 12.3 | | | | 15.5 | | | 9.1 | 3.2 | 1.6 | | 1.6 | 0.5 | 1.6 | 2.1 | 3.2 | 1.6 | 2.7 | 12.3 | 2.1 | 9.6 | 1.6 | | | | 99.8 | |
| N11 | | | D | 3 | 5 | 4 | 18 | 1 | | | 11 | 1 | | 13 | 1 | | | | | 4 | 2 | 1 | | 9 | 6 | 1 | 1 | | | | | | 81 | |
| | | | % | 3.7 | 6.2 | 4.9 | 22.2 | 1.2 | | | 13.6 | 1.2 | | 16 | 1.2 | | | | | 4.9 | 2.5 | 1.2 | | 11.1 | 7.4 | 1.2 | 1.2 | | | | | | 99.7 | |
| N10 | | | D | 9 | 23 | 11 | 14 | | 3 | | 24 | 1 | | 53 | 9 | | | | | 7 | 2 | 2 | 3 | 3 | 6 | 2 | 4 | | | | | | 182 | |
| | | | % | 4.9 | 12.6 | 6 | 7.7 | | 1.6 | | 13.2 | 0.5 | | 29.1 | 4.9 | 3.3 | | | 3.8 | 1.1 | 1.1 | 1.6 | 1.6 | 3.3 | 1.1 | 2.2 | | | | | | 99.6 | | |
| late Paleocene | N9 | | D | 5 | 19 | 5 | 7 | | 1 | 4 | 4 | 66 | 2 | | 50 | 16 | 6 | 6 | 2 | 8 | 3 | 1 | | | | | | | | | | | 205 | |
| | | | % | 2.4 | 9.3 | 2.4 | 3.4 | | 0.5 | 2 | 2 | 32.2 | 1 | | 24.4 | 7.8 | 2.9 | 2.9 | 1 | 3.9 | 1.5 | 0.5 | | | | | | | | | | | 100 | |
| | N8 | D | 6 | 14 | 13 | 12 | | | | | 5 | 52 | 3 | | 42 | 19 | 3 | 4 | 2 | | | | | | | | | | | | | | 175 | |
| | | % | 3.4 | 8 | 7.4 | 6.9 | | | | | 2.9 | 29.7 | 1.7 | | 24 | 10.9 | 1.7 | 2.3 | 1.1 | | | | | | | | | | | | | | 100 | |
| | N7 | D | 7 | 6 | | 2 | | | | | 1 | 18 | 2 | | 18 | 3 | 3 | 8 | 3 | | | | | | | | | | | | | | 71 | |
| | | % | 9.9 | 8.5 | | 2.8 | | | | | 1.4 | 25.4 | 2.8 | | 25.4 | 4.2 | 4.2 | 11.3 | 4.2 | | | | | | | | | | | | | | 100 | |
| | N6 | D | 16 | 11 | 4 | 7 | | 3 | | 13 | 38 | 1 | 2 | 43 | 2 | 4 | 17 | 5 | | | | | | | | | | | | | | | 166 | |
| | | % | 9.6 | 6.6 | 2.4 | 4.2 | | 1.8 | | 7.8 | 22.9 | 0.6 | 1.2 | 25.9 | 1.2 | 2.4 | 10.2 | 3 | | | | | | | | | | | | | | | 99.8 | |
| | N5 | D | 8 | 12 | 5 | 9 | | 7 | | 14 | 31 | 2 | 3 | 39 | 5 | 5 | | | | | | | | | | | | | | | | | | 140 |
| | | % | 5.7 | 8.6 | 3.6 | 6.4 | | 5 | | 10 | 22.1 | 1.4 | 2.1 | 27.9 | 3.6 | 3.6 | | | | | | | | | | | | | | | | | 100 | |
| | N4 | D | 9 | 16 | 2 | 4 | | 11 | 1 | 15 | 4 | 2 | 2 | 1 | 4 | | | | | | | | | | | | | | | | | | | 71 |
| | | % | 12.7 | 22.5 | 2.8 | 5.6 | | 15.5 | 1.4 | 21.1 | 5.6 | 2.8 | 2.8 | 1.4 | 5.6 | | | | | | | | | | | | | | | | | | 98.8 | |
| | NP7/8 | N3 | D | 18 | 19 | 8 | 7 | 2 | 3 | 3 | 4 | 7 | 1 | | | | | | | | | | | | | | | | | | | | | 72 |
| | | | % | 25 | 26.4 | 11.1 | 9.7 | 2.8 | 4.2 | 4.2 | 5.6 | 9.7 | 1.4 | | | | | | | | | | | | | | | | | | | | | 100 |
| N2 | | D | 28 | 18 | 9 | 6 | | 6 | 6 | 2 | 3 | | | | | | | | | | | | | | | | | | | | | | 78 | |
| | | % | 35.9 | 23.1 | 11.5 | 7.7 | | 7.7 | 7.7 | 2.6 | 3.8 | | | | | | | | | | | | | | | | | | | | | | 100 | |
| N1 | | D | 29 | 22 | 8 | 8 | | 14 | 5 | 1 | | | | | | | | | | | | | | | | | | | | | | | 87 | |
| | | % | 33.3 | 25.3 | 9.2 | 9.2 | | 16.1 | 5.7 | 1.1 | | | | | | | | | | | | | | | | | | | | | | | 99.9 | |

D: Number of species per 50 veivs *: Marker species

studied samples are generally abundant and well to moderately preserved. The stratigraphic distribution of the calcareous nannofossil species and biozones are presented in Fig. 3. Some of calcareous nannofossils are illustrated (Plates 1, 2).

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[illegible]

Fig. 3. Stratigraphic distribution of the calcareous nannofossil species at Wadi Nukhul, westcentral Sinai, Egypt

Fasciculithus spp. = *F. bitectus*, *F. stonehenge*, *F. bobii*, *F. richardi*, *F. tonii*, *F. thomasi* and *F. hayii*.

Rhombaster spp. = *R. cuspis*, *R. calcitrata* and *R. spineus*

A: abundant. >10 specimens/ 10 fields view, C: common=5-10 specimens/ 10 field view, F: few=2-4 specimens/ 10 field view, R: rare <2 specimens/ 10 field view.

(Preservation) G: good, M: moderate, P: poor.

| Age | | Formation | Sample No. | Abundance | Preservation | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|--------------|--------|-----------|------------|-----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--|
| | | | | | Nannofossil zones | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Sphenolithus primus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Ericsonia cava/ovalis/pelagica</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Ericsonia subpertusa</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Rhomboaster</i> spp. | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Campylophaera dela</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Discoaster binodosus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Discoaster multiradiatus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Discoaster diastypus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Discoaster barbadiensis</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Neochiastozygus junctus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Rhabdosphaera solus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Chiasmolithus bidens</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Tribrachiatius bramlettei</i> * (long arm) | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Tribrachiatius digitalis</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Ellipsolithus macellus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Chiasmolithus</i> spp. | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Tribrachiatius contortus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Pontosphaera multipora</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Chiasmolithus consuetus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Sphenolithus moriformis</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Tribrachiatius orthostylus</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Sphenolithus editus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Zygrhablithus bijugatus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Sphenolithus radians</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Sphenolithus conspicus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Toweius</i> spp. | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Discoaster lodoensis</i> * | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | <i>Neococcolithes dubius</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| early Eocene | Thebes | N50 | A | M | | C | R | R | | R | R | | | R | | C | | | F | F | | F | | C | R | F | F | C | R | F | R | R | |
| | | N49 | A | M | | C | R | R | | R | F | | | R | | C | | | F | F | | R | | C | R | F | F | C | | F | | R | |
| | | N48 | A | M | NP12 | C | R | R | | | F | | | R | | C | | | C | F | | R | | C | F | R | F | R | | F | R | R | |
| | | N47 | A | M | | C | R | R | | | F | | | R | | C | | | F | F | | R | | C | F | | F | R | R | | | R | |
| | | N46 | A | M | | C | R | R | | | F | | | R | | C | | | | F | | R | | C | C | | F | R | R | | | | |
| | | N45 | A | M | | F | | R | | | C | | R | | | C | | | F | C | | | | C | C | | F | R | R | F | R | | |
| | Esna | N44 | A | M | | F | R | | | R | C | | R | | | C | R | | | F | | R | | F | C | | R | R | | R | | | |
| | | N43 | A | M | | F | | | | | F | | R | R | | C | R | | | F | | | | R | C | | R | R | R | | | | |
| | | N42 | A | M | | R | F | F | | | F | | R | F | | F | | | F | F | | R | | F | C | | R | R | R | | | | |
| | | N41 | A | M | NP11 | R | F | F | | | R | | R | F | | F | | | R | F | | R | | F | C | | R | R | | | | | |
| | | N40 | A | M | | R | R | R | | | R | | | F | | F | | | | F | | F | | F | C | | F | R | | | | | |
| | | N39 | A | M | | R | R | R | | | R | | R | F | | F | | | | F | | R | | F | C | | F | R | | | | | |
| | | N38 | A | M | | F | R | R | | | F | | F | R | | F | | | | F | | R | | R | C | | R | R | | | | | |
| | | N37 | A | M | | F | R | R | | | F | | F | R | | R | | | | F | | R | | | C | | R | | | | | | |
| N36 | A | P | | C | C | F | | | F | | | | | R | R | | | F | | R | R | R | C | | R | | | | | | | | |
| Esna | N35 | A | P | | F | C | F | | | F | | | | R | R | | | F | R | R | R | R | R | F | | | | | | | | | |
| | N34 | A | G | NP10d | R | F | F | | | F | | R | | R | F | R | | R | C | F | R | | R | R | | | | | | | | | |
| | N33 | A | M | | R | R | R | | | R | | | R | R | | | | F | F | R | | R | | | | | | | | | | | |
| | N32 | A | M | | R | R | R | | | R | R | | R | R | R | | R | | F | F | R | R | R | | | | | | | | | | |
| | N31 | A | M | | R | R | R | R | | R | R | | R | R | R | | R | | F | R | | | | | | | | | | | | | |
| | N30 | A | G | | ** | R | F | R | R | | F | F | R | R | R | F | | R | | F | # | | | | | | | | | | | | |
| | N29 | A | G | * | F | F | F | R | R | F | R | R | R | R | F | R | R | R | | | | | | | | | | | | | | | |

Rhomboaster spp. = R. cuspidis, R. intermedia & R. Bitrifida

= Tribrachiatius cf. contortus

* = NP10b

**=NP10c

Fig. 3. Continued

Plate (1)

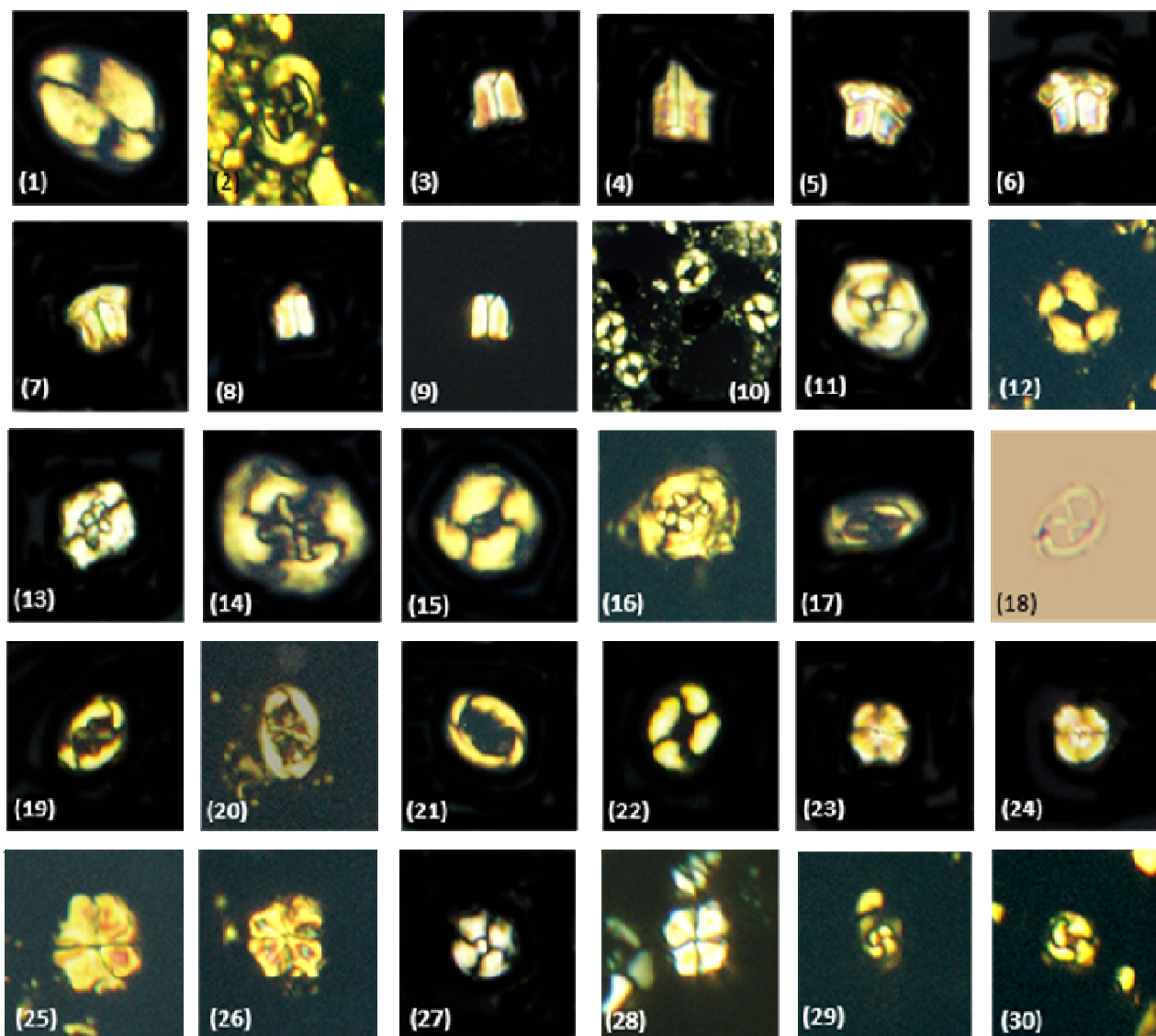
— 10 μ m

Plate (1). (1) *Pontosphaera multipora*, N17. (2) *Cruciplacolithus* spp., N23. (3) *Fasciculithus tympaniformis*, N7. (4) *Fasciculithus lillianae*, N9. (5-7) *Fasciculithus bitectus*, N4. (8-9) *Fasciculithus aubertae*, N4. (10-12) *Chiasmolithus* spp., (10-11) sample N6, (12) Sample N13. (13-14) *Chiasmolithus danicus*, (13) sample N4, (14) sample N20. (15) *Chiasmolithus consuetus*, N19. (16) *Chiasmolithus bidens*, N19. (17) *Campylosphaera dela*, N19. (18-19) *Neochiastozygus modestus*, N11. (20-21) *Neochiastozygus junctus* (20) Sample N19, (21) sample N13. (22) *Ericsonia* cf. *formosa*, N25. (23-24) *Bomolitus elegans* / *Bomolitus conicus*, N4. (25-26) *Sphenolithus moriformis* (25) Sample N50 (26) Sample N45. (27) *Cyclagelosphaera* cf. *reinhardtii* N1. (28) *Sphenolithus primus* N50. (29) *Toweius* spp., N50. (30) *Reticulofenestra* cf. *dictyoda* N50.

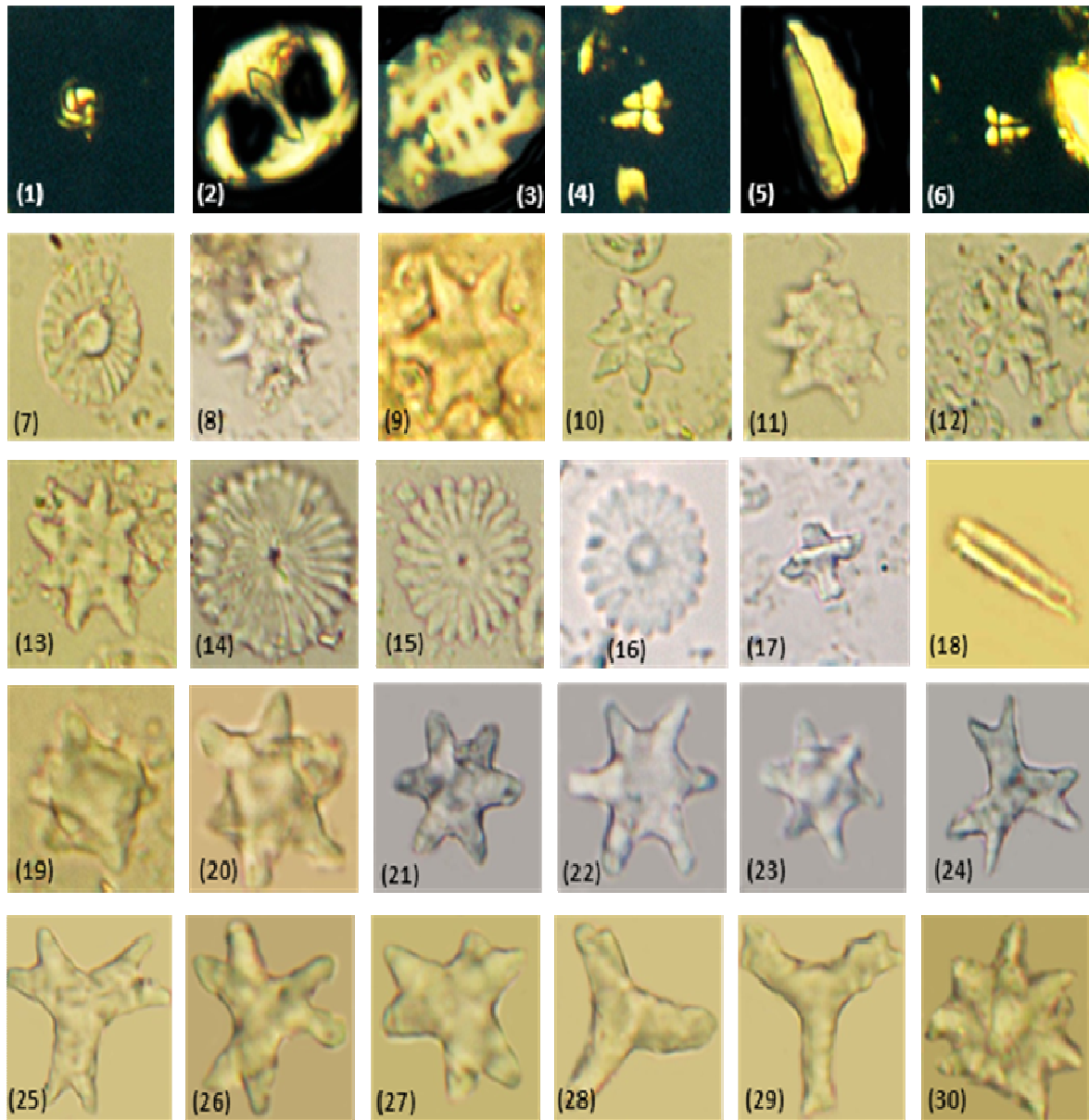
Plate (2) — 10 μ m

Plate (2). (1) *Reticulofenestra* cf. *dictyoda*, N50. (2) *Zygodiscus adams*, N30. (3) *Ellipsolithus distichus*, N30. (4) *Sphenolithus editus*, N49. (5) *Zygrhablithus bijugatus*, N21. (6) *Sphenolithus radians*, N49. (7) *Discoaster megastypus* N7. (8-9) *Discoaster mahmoudii* (8) sample N9, (9) Sample N11. (10-13) *Discoaster araneus*, (10-12) sample N6 (13) sample N7. (14-16) *Discoaster multiradiatus*, N9. (17) *Discoaster diastypus*, N17. (18) *Rhabdosphaera solus*, N15. (19) *Rhomboaster intermedia*, N17. (20) *Rhomboaster bitrifida*, N15. (21-23) *Tribrachiatus bramlettei*, (21) sample N20, (Short arm), (22) sample N27 (Long arm), (23) sample N20 (Short arm). (24-25) *Tribrachiatus digitalis* (24) sample N34 (25) sample N29. (26-27) *Tribrachiatus contortus*, N34. (28-29) *Tribrachiatus orthostylus*, N40. (30) *Discoaster lodoensis*, N45.

3.1. *Discoaster Mohleri* Zone (NP7/8) (Hay, 1964) Emended by (Romein, 1979)

Zones NP7 and NP8 are difficult to be differentiated in case of the absence of the marker species *Heliolithus riedelii* at the top of Zone NP7 (Romein, 1979). The base of this interval is defined at the first appearance of *Discoaster mohleri* where its top is defined at the first appearance of *Discoaster multiradiatus*. It is represented by samples N1 to N3 with total thickness of about 2.0m.

In east central Sinai, Zone NP7/8 was recorded by (Faris and Abu Shama, 2007) from the hard yellowish brown limestone stringer (1m) intercalating the Esna Formation at Gebel Mishiti. The calcareous nannofossil assemblages are well to moderately preserved and they are abundant. *Discoaster okadi*, *Ericsonia robusta* and *Discoaster nobilis* are recorded from the top of this zone. The upper part of this zone displays common abundance of genera *Fasciculithus*; *Sphenolithus* and *Ericsonia* (Fig.4). These taxa reflect relatively warm and, probably oligotrophic surface water

(Khozyem et al., 2013).

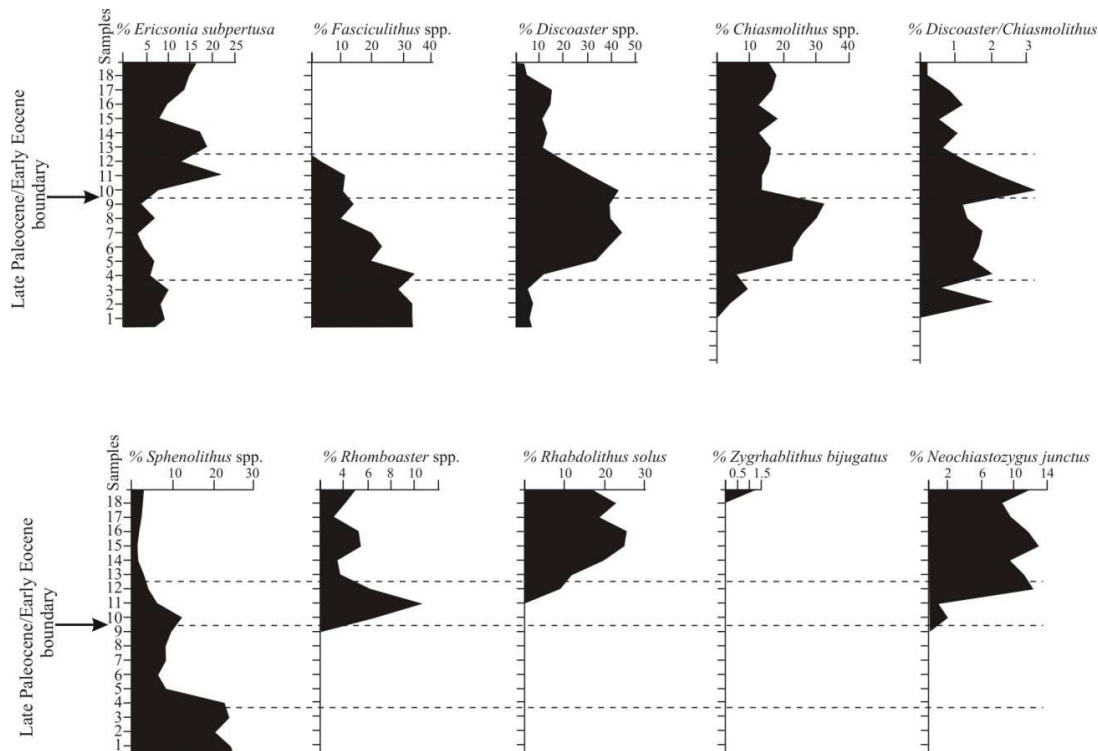


Fig. 4. Relative abundance of selected calcareous nannofossil assemblage across the Paleocene/Eocene boundary, Wadi Nukhul, westcentral Sinai, Egypt.

3.2. *Discoaster Multiradiatus* Zone (NP9) (Bramlette and Sullivan, 1961) Emended by (Martini, 1971) and (Bukry and Bramlette, 1970)

The base of this zone is well defined by the first appearance of *Discoaster multiradiatus* where its top is marked by the first appearance of *Tribrachiatus bramlettei*. In the absence of the primary index species for NP10, the top of this zone is provisionally placed at the last appearance of *Fasciculithus involutus* following Perch-Nielsen 1985. However, in the present study few reworked specimens of *F. involutus* and other *Fasciculithus* spp. are recorded from the base of Zone NP10 in association with *Tribrachiatus bramlettei*. Zone NP9 is represented here at the lower part of the Esna Formation (6.0m thick).

Perch-Nielsen (1985) suggested that Paleocene diversity reached a maximum in Zone NP9. The present study agrees with this statement because of 21 incoming species characteristic of the Paleocene have their first appearances in this zone (Fig.3).

In Zone NP9, *Rhomboaster* evolved and radiated and *Discoaster araneus* had a short range within NP9 and the basal part of NP10. Aubry et al. (1999) subdivided the *Discoaster multiradiatus* Zone (NP9) into two subzones (NP9a and NP9b) based on the first appearances of *Rhomboaster* and/or *Discoaster araneus*. This level was adopted by the International subcommission on Paleogene Stratigraphy (ISPS) as one of the most important events which characterize the Paleocene/Eocene boundary interval.

In the present study, the lower boundary of the Subzone NP9b is put below sample N10 (brownish calcarenite) which

reveals the first appearances of *Rhomboaster* spp. and *D. araneus*. The acme of *Ericsonia Subpertusa* is recorded in the middle part of Subzone NP9b whereas first appearance of *Rhabdosphaera solus* and the increase abundance of *Neochiastozygus junctus* characterize its topmost part. The last appearance of *Fasciculithus alanii* is coincided with the NP9a/NP9b subzonal boundary. However, *Fasciculithus alanii* is recorded slightly above the NP9a/NP9b subzonal boundary in the Dababiya section, Nile Valley (Aubry et al., 1999), and in Gebel Mishiti, west central Sinai (Faris and Abu Shama, 2007).

3.3. *Tribrachiatus Contortus* Zone (NP10), (Hay, 1964) and (Bukry, 1973)

This zone includes the biostratigraphic interval from the first appearance of *Tribrachiatus bramlettei* to last appearance of *Tribrachiatus contortus*. It covers large portion of the Esna Formation of about 13.0m thick. In this study the base of NP10 is delineated by the first appearance of *T. bramlettei* and *D. diastypus*. Other taxa were introduced throughout this zone such as *Zygrhablithus bijugatus*, *Chiasmolithus bidens*, *Chiasmolithus consuetus*, *Discoaster barbadiensis*, *Tribrachiatus digitalis*, *Pontosphaera multipora*, *Campylosphaera dela* and *T. cf. contortus* and *T. contortus*. The first appearance of *Tribrachiatus orthosrylus* is recorded in the topmost part of Zone NP10. It overlaps with *T. contortus* and their arms have slight bifurcation (Type A). It seems that the early forms of this species are a morphotype transitional between *T. contortus* and *T. orthostylus*.

The basal part of Zone NP10 is characterized by high

abundance of *Neochiastozygus junctus* and *Rhabdosphaera solus*. This event can be used to delineate the base of Zone NP10 in case of absence of *T. bramlettei*. The short-lived *Rhomboaster* spp. that generally occurs in Subzone NP9b is recognized here overlaps 0.5m with *T. contortus*. Similar overlap between the *R. cuspis* group and the *T. contortus* is recorded at ODP Site 1215 (Raffi et al., 2005).

According to (Aubry, 1996) Zone NP10 is divided into four subzones based on sequential appearances of the different species of *Tribrachiatus*: 1) Subzone NP10a (*T. bramlettei*-*T. digitalis* Subzone) is defined as the interval between the first appearance of *T. bramlettei* and the first appearance of *T. digitalis*; 2) Subzone NP10b (*T. digitalis* Subzone) is defined by the total range of the *T. digitalis*; 3) Subzone NP10c (*T. digitalis*-*T. contortus* Subzone) is the interval between the last appearance of *T. digitalis* and the first appearance of *T. contortus*; 4) Subzone NP10d (*T. contortus* Subzone) is defined by the total range of *T. contortus*. In this study, the four subzones NP10a to NP10d were recorded.

The total thicknesses of these Subzones are 8m, 1.5m, 0.5m and 3.0m, respectively. Subzones NP10b and NP10c are to lesser thicknesses compared with NP10a and NP10d. This may be interpreted if a small hiatus between the subzones NP10b and NP10c might had occurred. A minor hiatus was recorded in Gebel Mishiti section, west central Sinai slightly after the beginning of the early Eocene due to the missing of subzones NP10b and NP10c (Faris and Abu Shama, 2007). However, the reduced thickness of subzones NP10b and NP10c in the Wadi Nukhul may be a normal because, 1) The *T. digitalis* morphotype (its total range = Subzone NP10b) is often reported from only a few samples in each section investigated (e. g. Aubry 1996; Aubry et al. 1996; Cramer et al. 2003 and Dupuis et al. 2003), 2) The recorded thickness of NP10b (1.5m), about one sixth of the thickness of NP10a (8.0m), is large if compared with thickness of NP10b at the proposed P/E GSSP section of Dababiya in Egypt (Dupuis et al., 2003).

Subzone NP10b (*T. digitalis* Subzone) is defined by the total range of the *T. digitalis*. However, in the upper part (sample N34) of Subzone NP10d, forms of *T. cf. digitalis* as well as rare of *T. digitalis* similar forms are abnormally recorded overlaps the early forms of *T. orthostylus*. *T. digitalis* morphotype and its ranges (Aubry, 1996) are subjected to criticisms from (Raffi et al., 2005). At Wadi Nukhul, it is noted that the arms of the morphotype *T. cf. digitalis* seems rounded whereas the proper morphotype *T. digitalis* is flattened in plane light. More investigations are need by SEM for discrimination between these forms.

3.4. *Discoaster Binodosus* Zone (=NP11) (Mohler and Hay in Hay et al., 1967)

The last appearance of *Tribrachiatus contortus* defines the base of this zone where its top is defined by the first appearance of *Discoaster lodoensis*. The thickness of this zone covers about 5.5m in the studied section. It is represented by samples N36-N44 of grey nodular marlstone which consist the uppermost of the Esna Formation.

Calcareous nannofossils here are abundant but moderately preserved. *Sphenolithus editus*, *S. radians*, *S. conspicuous* and *Toweius* spp. are the incoming early Paleocene taxa in this zone. *T. orthostylus* is common and two forms of this taxon are recorded; rare of form A (have three arms with slight bifurcation) and frequent abundance of form B (no bifurcation in the arms).

3.5. *Tribrachiatus Orthostylus* Zone (NP12) (Brönnimann and Stradner, 1960)

This zone includes the biostratigraphic interval between the first appearance of *Discoaster lodoensis* and the last appearance of *Tribrachiatus orthostylus*. It is defined at sample N45 by badly preserved *Discoaster lodoensis* specimens. Despite of a diligent search for samples across the low part of NP12, only very rare specimens were sparsely recorded because of *D. lodoensis* is affected by heavy overgrowth and thus will be there difficulty to identify. *Sphenolithus radians* and *S. conspicuous* appear close to the top of Zone NP11 respectively and can be used as provisional marker to trace the NP11/NP12 zonal boundary. On the other hand, *Neococcolithes dubius* that generally appears in the basal part of Zone NP12 is recorded in N47 whereas first appearance of *Sphenolithus conspicuous*, that generally appears in the uppermost part of Zone NP11, occurs in N42. Consequently, the lower boundary of Zone NP12 must be found between these two events (between samples N42 and N47). Therefore, the poorly preserved *Discoaster lodoensis* specimens in N45 can delineate the base of Zone NP12.

4. The P/E stage Boundary

The Carbon Isotopes Excursion (CIE) has been used to delineate the Paleocene/Eocene boundary worldwide (Ouda and Aubry, 2003). Associated with this event is a benthic foraminiferal extinction event in deep-sea records, a turnover in mammalian fauna in terrestrial records, and the appearance of excursion taxa in both planktic foraminifera and calcareous nannofossils. Changes in the biotic realm are a reflection of rapid and extreme paleoceanographic changes that point to a greenhouse world characterized by increased temperature and precipitation.

According to (Dupuis et al., 2003) the Paleocene/Eocene boundary can be located between Subzones NP9a and NP9b at the base of a thin dark gray clayey layer which is considered as a part of the Esna Formation. At Matulla and Abu Zenima sections (westcentral Sinai), (Bolle et al., 2000) did not differentiate subzones of NP9 and they placed the Paleocene/Eocene boundary in the basal part of the Esna Formation between the Zone NP9 and the Subzone NP10a. In east central Sinai, the P/E boundary was delineated by (Faris and Abu Shama, 2007) at Gebel El Mishiti between Subzones NP9a and NP9b based on the first appearances of *Rhomboaster calcitrapa*, *R. cuspis*, *R. bitrifida* and *Discoaster araneus*. In the present work, this boundary is also placed at the NP9a/NP9b subzonal boundary which corresponds to a brownish calcarenite bed, sample N10. This sample reveals

the first appearances of *Rhomboaster* spp. and *D. araneus*.

5. Calcareous Nannofossil Assemblages and Paleocology at the P/E Transition

The Paleocene/Eocene (P/E) transition is often referred as the Paleocene Eocene Thermal Maximum (PETM; ~55 Ma). This interval is associated with a major turnover in benthic and planktonic marine communities (e.g., Thomas and Shackleton, 1996; Kelly et al., 1996, 1998; Bralower, 2002). About of the response of the calcareous nannoplankton to the PETM event, there have been some investigations (e.g., Aubry, 1998; Bralower, 2002; Tremolada and Bralower, 2004; Raffi et al., 2005, 2009; Raffi and De Bernardi, 2008; Bown and Pearson, 2009; Jiang and Wise Jr., 2009; Khozyem et al., 2013).

In the studied section, quantitative investigations of calcareous nannofossil assemblages were performed on the interval from NP7/8 to the basal part of NP10 across the PETM (spans NP9b). The Paleocene Eocene Thermal Maximum (PETM) in the present section can be subdivided into a lower part and an upper part on the basis of the nannofossil assemblages. The abrupt changes in the nannofossil assemblages in the lower and upper parts of the PETM (Fig.4) suggest that nannoplankton communities were not stable and that surface water conditions changed over the course of the event. The changes in the abundance of the calcareous nannofossil assemblages can be interpreted as a response to palaeocologic conditions such as paleotemperature and paleofertility. It was suggested that taxa were adapted to eutrophic upwelling environments should be common in cold-water assemblages; likewise, oligotrophic taxa are likely to be more common in warm-water assemblages that thrived in a stable water column (Haq et al., 1977; Wei and Wise, 1990; Aubry, 1992, 1998; Bown and Pearson, 2009).

Ericsonia subpertusa (*Coccolithus subpertusus*) which is common in the basal part of Subzone NP9b becomes acme slightly above (10cm) the brownish calcarenite bed. Although, slight drop in the abundance of this species is present in the topmost part of Subzone NP9b, it again becomes acme in the base of NP10a. *Ericsonia* is thought to be a warm-water indicator (Wei and Wise, 1990; Kelly et al., 1996; Bown and Pearson, 2009). Its absence at high latitudes and its common association with *Discoaster* indicate a similar affinity for warm oligotrophic environments (Bralower, 2002). The acme of *E. subpertusa* (*C. subpertusus*) was recorded at the Dababyia section by (Dupuis et al., 2003) in the bed DBH 2.3 with the first appearances of *D. anartios* and the long-armed species of *Rhomboaster* (the base of NP9b) and coincide with the minimum (negative) $\delta^{13}\text{C}$ value of the CIE. They correlated this acme with that of this species at the Equatorial Pacific Ocean Drilling Site 865 (Kelly et al., 1996) in which case this is a global acme possibly is response in global warming.

At Wadi Nukhul section, common abundance of the Paleocene genus *Fasciculithus* that mainly represented by

Fasciculithus tympaniformis characterizes the Zone NP7/8. In the higher Subzone NP9a, genus *Fasciculithus* diversified and other *Fasciculithus* species of low abundance are displayed with *F. tympaniformis*. However, the relative abundance of genus *Fasciculithus* gradually decreases from about 38% in the lower part of Subzone NP9a to about 12% at its top part. The relative abundance of genus *Fasciculithus* reached to about 10% in the lower part of the PETM and became extinct close to its upper part where the relative abundance of the *Fasciculithus* sharply decreased to less than 2%. The sharp decrease of *Fasciculithus* across the PETM interval was accompanied by decreases in its diversity.

The final decline in *Fasciculithus* corresponding to an abrupt increase in the abundance of the genus *Zygrhablithus* as well as the abundance cross-over between the two genus has been observed to occur within the CIE-PETM interval in several deep-sea sections (Bralower, 2002; Tremolada and Bralower, 2004). Data from this study do not show any *Z. bijugatus* across the PETM interval. The sudden evolution and influx of *Z. bijugatus* and the linked abundance cross-over with *Fasciculithus* spp. is not observed in the proposed P/E GSSP section of Dababyia in Egypt (Dupuis et al., 2003). Therefore, lack of the holococcolith genus *Zygrhablithus* across the PETM interval is a conspicuous character in the Tethys realm. The early Eocene substitution of *Fasciculithus* by *Zygrhablithus* is also absent in equatorial regions (Raffi et al., 2005).

Although, the ecological affinities of *Fasciculithus* is not well known (Haq and Lohmann, 1976) found an inverse correlation of this genus with *Prinsius martinii*, a species that was concentrated in high latitude, more eutrophic environments. (Bralower, 2002) interpret *Fasciculithus* as K mode specialist that was adapted to warmer, more oligotrophic environments. *Zygrhablithus bijugatus* was interpreted as an oligotrophic deep-dwelling species by (Aubry, 1998). However, the *Fasciculithus* spp./*Z. bijugatus* abundance cross-over was interpreted as a change from oligotrophic to cooler and more eutrophic conditions (Tremolada and Bralower, 2004).

In the lower part of the PETM of the present work, a secondary sharp decrease of *Fasciculithus* spp. was in conjunction with increase of *Rhomboaster* spp. (Raffi et al., 2005) recognized that the demise of *Fasciculithus* occurs concomitantly with the initial rise or marked abundance increase of the non-spined rhomboasters (*R. cuspsis*). It is suggested that the *Rhomboaster-D. araneus* association showed strong provincialism, being geographically restricted to the Tethys seaway, the North and South Atlantic oceans, and the westernmost Indian Ocean (Aubry, 2001; Kahn and Aubry, 2004). The studied samples reveal an increase in the abundance of the cool water taxa *Neochiastozygus junctus* and *Rhabdolothus solus* is concomitant with the final elimination of *Fasciculithus* spp. (Fig. 4). Then the niche of *Fasciculithus* spp. was filled by the cooler and more eutrophic taxa in the upper part of the PETM interval due to the environmental changes.

The abundance of *Discoaster* spp. sharply increases during

the Subzone NP9a but was followed by slight decrease at the top of this subzone. However the onset of *Discoaster* spp. in the lower part of the PETM interval was followed by sharp decrease in its upper part. The *Discoaster* spp reflect relatively warm water (Wei and Wise, 1990) and, probably, oligotrophic surface waters (Aubry, 1992).

Abundance of the genus *Chiasmolithus* -an indicator of relatively cool and eutrophic water- decreased dramatically across the P/E boundary. On the other hand, the ratio of *Discoaster/Chiasmolithus* sharply increased in the lower part of the PETM interval (Fig. 4) indicating prevalence warm oligotrophic conditions. *Chiasmolithus* increases again than the *Discoaster* since the upper part of the PETM interval.

Sphenolithus are abundant throughout the combined Zone NP7/8 and their abundance are steady common in Subzone NP9a. The sharp increase in the abundances of *Sphenolithus* in the calcareite bed was followed by pronounced decrease in its abundance in the upper part of the PETM interval up to Zone NP10. The ecological affinities of *Sphenolithus* is not well known. However, (Bralower, 2002) interprets *Sphenolithus* as K mode specialists that was adapted to warmer, more oligotrophic environments.

6. Summary and Conclusions

Calcareous nannofossils were studied in Esna and the base of the Thebes formations at Wadi Nukhul, westcentral Sinai, Egypt. Six nannofossil zones were recorded (NP7/8, NP9, NP10, NP11 and NP12). NP9 Zone can be subdivided into two subzones and the four subzones of NP10 were recognized. The basal part of Zone NP10 is characterized by high abundance of *Neochiastozygus junctus* and *Rhabdosphaera solus*. This event can be used to delineate the base of Zone NP10 if *T. bramlettei* is absent.

Nannofossil data indicates that the Esna Formation conformably underlies the Thebes Formation. The Paleocene/Eocene boundary is placed at the NP9a/NP9b subzonal boundary at which the first appearances of *Rhomboaster* spp. and *D. araneus* corresponds a brownish calcarenite bed (sample N10).

The nannofossil assemblage data can be used to provide information on temperature, productivity, and the thermal structure of the upper water column through the PETM interval. This interval can be subdivided into a lower part and an upper part on the basis of the nannofossil assemblages.

The abrupt changes in the nannofossil assemblages in the lower and upper parts of the PETM suggest that nannoplankton communities were not stable and that surface water conditions changed over the course of the event. *Ericsonia* is thought to be a warm-water indicator and indicates for oligotrophic environments. The acme of *Ericsonia subpertusa* (*Coccolithus subpertusus*) was recorded in the lower part of PETM interval in concomitant with *Rhomboaster*.

The niche of *Fasciculithus* spp. was filled by *Neochiastozygus junctus* and *Rhabdolithus solus*-the cooler and more eutrophic taxa- in the upper part of the PETM interval

due to the environmental changes. The lack of the holococcolith genus *Zygrhablithus* across the PETM interval is a conspicuous character in the studied section as well as in the Tethys realm.

The *Discoaster* spp. reflect relatively warm water and, probably, oligotrophic surface waters. The onset of *Discoaster* spp. in the lower part of the PETM interval was followed by sharp decrease in its upper part. The abundance of the genus *Chiasmolithus* -an indicator of relatively cool and eutrophic water- decreased dramatically across the P/E boundary. On the other hand, the ratio of *Discoaster/Chiasmolithus* sharply increases in the lower part of the PETM interval indicating prevalence warm oligotrophic conditions. *Chiasmolithus* increases again than the *Discoaster* since the upper part of the PETM interval.

The fluctuations in the relative abundance between warm-water and cool-water species can be adopted to infer the climatic fluctuations during the PETM event. The major assemblage shift across the P/E boundary suggests a change from colder, more productive surface waters to warmer, more oligotrophic conditions.

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