Environmental perturbation in the southern Tethys across the Paleocene/Eocene boundary (Dababiya, Egypt): Foraminiferal and clay mineral records

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Abstract

Foraminiferal and clay mineral records were studied in the upper Paleocene to lower Eocene Dababiya section (Egypt). This section hosts the GSSP for the Paleocene/Eocene boundary and as such provides an expanded and relatively continuous record across the Paleocene/Eocene Thermal Maximum (PETM). Deposition of illite–smectite clay minerals is interpreted as a result of warm and arid conditions in the southern Tethys during the latest Paleocene. Benthic foraminiferal assemblages are indicative of seasonal variation of oxygen and food levels at the seafloor. A sea-level fall occurred in the latest Paleocene, followed by a rise in the earliest Eocene. Foraminiferal diversity and densities decreased strongly at the P/E boundary, coinciding with the level of global extinction of benthic foraminifera (BEE) and start of the Carbon Isotope Excursion (CIE) and PETM. In the lower CIE, the seafloor of the stratified basin remained (nearly) permanently anoxic and azoic. A sudden increase in mixed clay minerals (kaolinite and others) suggests that warm and perennial humid conditions prevailed on the continent. High levels of TOC and phosphathic concretions in the middle CIE are evidence for increased organic fluxes to the sea floor, related to upwelling and to augmented continental runoff. Low densities of opportunistic taxa appeared, indicating occasional ephemeral oxygenation and repopulation of the benthic environment. The planktic community diversified, although conditions remained poor for deep-dwelling taxa. An increase in illite–smectite dominated clay association is considered to mark the return of a seasonal signature on climatic conditions. During the late CIE environmental conditions changed to seasonally fluctuating mesotrophic conditions and diverse and rich benthic and planktic foraminiferal communities developed. Post-CIE planktic faunas consisted of both deep and shallow-dwelling taxa and buliminid-dominated benthic assemblages reflect fluctuating mesotrophic conditions.

The frequent environmental perturbations during the CIE/PETM at Dababiya provided a rather specialized group of foraminiferal taxa (i.e., Anomalinoïdes aegyptiacus) the opportunity to repopulate, survive and subsequently dominate by a hypothesized capacity to switch to an alternative life strategy (population dynamics, habitat shift) or different metabolic pathway. The faunal record of Dababiya provides insight into the cause and development of the BEE: various severe global changes during the PETM (e.g., ocean circulation, CaCO3-dissolution, productivity and temperature changes) disturbed a wide range of environments on a geologically brief timescale, explaining together the geographically and temporally variable character of the BEE.

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1. Introduction

The transition from the Paleocene to the Eocene is characterized by a number of exceptional events, collectively known as the Paleocene/Eocene Thermal Maximum (PETM), a transient period of global warmth at 55 Ma (Kennett and Stott, 1991; Zachos et al., 1993). A global drop in δ13C values of up to 2–3‰, known as the Carbon Isotope Excursion (CIE), marks the onset of the PETM during which within a few thousand years global temperatures rose by 5–8 °C, (Kennett and Stott, 1991; Koch et al., 1995; Corfield and Norris, 1998; Jenkyns, 2003). The PETM is the best-studied period in the Earth’s pre-Quaternary history, in which rapid climate change took place, and it is thought to be a good analogue for climatic changes the Earth is facing today (Dickens, 1999). Study of the PETM enables an assessment of the interaction between geosphere and biosphere during rapidly occurring climatic perturbations and provides insight into the return to background conditions (Bains et al., 2000; Schmitz, 2000).

The release of a massive amount of methane from gas hydrates from the seafloor is generally held responsible for the dramatic climate change during the PETM (Dickens et al., 1995; Katz et al., 1999; Dickens, 2004). The strong negative shift in δ13C (CIE) is presently explainable only by the release of very light methane (~ −60‰ 13C), although the trigger for the release of methane is still a point of debate (e.g., Eldholm and Thomas, 1993; Dickens et al., 1995; Kent et al., 2003; Svensen et al., 2004; Cramer and Kent, 2005).

The effect of globally rising temperatures on ocean productivity during the PETM is an issue of debate. Several oceanic records suggest widespread oligotrophy (Kelly et al., 1996; Bralower, 2002), although most continental margin records and some open ocean records suggest an increase in productivity (e.g., Crouch et al., 2001; Speijer and Wagner, 2002; Gavrilov et al., 2003; Stoll and Bains, 2003).

A global increase in kaolinite during the PETM (Robert and Kennett, 1992) is interpreted as a period of global warm and perennial humid conditions (Robert and Chamley, 1991). However, within the Tethyan realm clay mineral records give evidence for differentiated climate zones (Bolle et al., 2000a; Bolle and Adatte, 2001). Lower Paleocene sediments from Tunisia, Spain, Israel and Egypt contain abundant kaolinite, considered to point at warm and perennial humid conditions (Bolle and Adatte, 2001). Along the southern margins of the Tethys however, conditions became progressively drier from the late Paleocene to Eocene, indicated by the increased deposition and formation of minerals such as palygorskite and sepiolite (Bolle and Adatte, 2001; Shoval, 2004). During the PETM the southern margins of the Tethys were arid with high evaporation rates (Bolle et al., 2000b; Shoval, 2004; Khormali et al., 2005), although warm and humid conditions may have persisted on the African continental hinterland (Bolle and Adatte, 2001). However, the paleoenvironmental interpretation of clay minerals is not always straightforward and has shown to potentially yield complex and mixed signals, for instance because of the attribution of weathered minerals from different climate zones in the drainage area of rivers (Thiry, 2000). Therefore, paleoenvironmental implications based on clay minerals should be made carefully and preferably in combination with other proxies, as done in this paper.

The climate change triggered many faunal and floral radiations and migrations in both continental and marine settings (Kelly et al., 1998; Clyde and Gingerich, 1998; Aubry, 1998; Oreshkina and Oberhänsli, 2003; Speijer and Morsi, 2002). In the deep-sea, however, a major extinction took place among the benthic foraminifera (Tjalsma and Lohmann, 1983; Kennett and Stott, 1995; Thomas, 1998; Thomas et al., 2000). This benthic foraminiferal extinction event (BEE) yielded high extinction rates of ~40% and locally up to 65% in the deep-sea (Beckmann, 1960; Thomas, 1990; Kairo, 1994). In the southern Tethys, the extinction event was similarly severe at upper bathyal sites in Sinai (Egypt) and in southern Israel (Speijer, 1995), but it had less impact at middle to outer neritic depths where estimated extinction rates range up to 25% (Speijer et al., 1995, 1996). Paleocene benthic foraminiferal faunas were to a
large extent cosmopolitan and two principal assemblages can be distinguished. The first is the so-called Midway-type fauna, typical of continental shelf environments, and the second is the Velasco-type fauna, representative of continental slope to abyssal environments (Berggren and Aubert, 1975). Many individual taxa had quite broad bathymetric ranges (Tjalsma and Lohmann, 1983) and in upper slope environments in the Tethys, the Midway and Velasco end-members grade into each other (Speijer, 1995). The benthic extinction event occurred so rapidly that it is difficult to compare the immediate post-extinction faunas on a global scale, since the extinction level often coincides with an unconformity and/or with carbonate-dissolution intervals with poor recovery of calcareous foraminifera in deep-sea cores (Thomas, 1998). Another problem is that the taxonomy of the post-extinction faunas is not yet fully comparable and no clear consensus exists between various authors (Thomas, 1998). Although early Eocene faunas appear to be less cosmopolitan and a higher differentiation existed in geographical distributions, some general assemblage patterns can be identified. For instance, benthic foraminiferal assemblages composed of Nuttallides truempyi and Oridorsalis umbonatus dominate abyssal sites in the North and South Atlantic and Pacific Oceans and are thought to be representative of oligotrophic conditions (e.g., Miller et al., 1992). At bathyal depths post-extinction faunas are dominated by buliminids at various sites in the Atlantic, Pacific and Tethyan regions and these assemblages are considered to indicate low-oxygen and/or high productivity conditions (Thomas and Gooday, 1996; Thomas and Shackleton, 1996).

1.1. Previous studies

The numerous and excellent lower Paleogene outcrops in Egypt and the many stratigraphic and paleoenvironmental studies carried out on them paved the way for the selection of the Dababiya Quarry section near Luxor in the Nile Valley to host the global boundary stratotype section and point (GSSP) for the Paleocene/Eocene boundary (Ouda and Aubry, 2003). Relative to other well-known sections in the region, the Dababiya section offers an expanded marine succession of the PETM, which can be studied in three dimensions along several faces of the quarries (Ouda and Aubry, 2003). The δ13Corg record supports the idea that the Dababiya H subsection comprises a fairly continuous record of the CIE, whereas the Midway-type benthic foraminiferal assemblages reflect outer neritic deposition (Dupuis et al., 2003).

During the final preparation of this manuscript another study on the benthic foraminifera of the Dababiya H section became available (Alegret et al., 2005), which inferred that the benthic foraminiferal patterns reflect persisting environmental stress (oxygen deficiency, carbonate dissolution, changes in food supply) during most of the CIE interval. In general, our observations are conformable with this study. However, there are significant differences between our data set and paleoenvironmental interpretation and those of Alegret et al. (2005), which address in more detail in the discussion (Section 4.1). Even though lithological, planktic and benthic foraminiferal records of the Dababiya H section have been published (Berggren and Ouda, 2003; Dupuis et al., 2003; Alegret et al., 2005), a comprehensive and detailed paleoenvironmental reconstruction combining several paleoenvironmental indicators is still lacking. In this paper, we reconstruct the changes in the paleoenvironmental setting that occurred during the Paleocene/Eocene transition in the Dababiya area by combining faunal, lithological and clay mineral data. We expanded the number of studied samples in the CIE interval compared to Dupuis et al. (2003). Further, we provide more ecological detail in the benthic foraminiferal record compared to Alegret et al. (2005), by studying the 63–125 and the 125–630 μm size fractions separately and by considering the importance of foraminiferal densities.

2. Material and methods

2.1. Location

The Dababiya section (25°30′N, 32°31′E) is located on the right (east) bank of the upper Nile Valley (Fig. 1a). This section is a composite section, consisting of four partially stratigraphically overlapping sections; this study is focused on section H (Dupuis et al., 2003) comprising the GSSP of the basal Eocene (Fig. 1b). In 2004, the “Golden spike” (actually made of stainless steel) marking the GSSP was placed at the base of the non-calcareous clay of Dababiya Quarry bed 1. Unfortunately, a visit in January 2006 revealed that the spike had been removed from the outcrop. Its former position is now merely marked by a distinct hole.

2.2. Stratigraphy, lithology and clay mineralogy

A detailed description of the lithology of the Dababiya H subsection is given in Dupuis et al. (2003) and the stratigraphy in Fig. 2 is based on this paper. The base of the Dababiya H subsection is
composed of the uppermost part of the Esna 1 unit (−1.85 to 0.00 m). It is composed of marly shales with carbonate contents of 25–50%. Above the P/E boundary, the base of the Esna 2 unit comprises a set of five beds: the Dababiya Quarry Beds (DQ-beds). The DQ-beds in the Dababiya H subsection are in total 3.68 m thick and show the most expanded succession of the base of the Esna 2 unit in the region (Dupuis et al., 2003). Five beds are distinguished lithologically: DQ-bed 1 (0.00–0.63 m): a dark laminated non-calcareous clay with at the base a few phosphatic coprolites. DQ-bed 2 (0.63–1.13 m): phosphatic brown shale with numerous coprolites, with increasing carbonate content (up to 30%). DQ-bed 3 (1.13–1.97 m): a light-colored laminated phosphatic shale with some coprolites and many phosphate inclusions; the carbonate content varies between 30 and 35%. DQ-bed 4 (1.97–2.68 m): grey shale with increasing carbonate content (40–50%). DQ-bed 5 (2.68–3.68 m): a light-grey marly calcarenitic limestone with high carbonate content (~50–70%).

Above the DQ-beds (3.68–4.58 m), the Esna 2 unit continues as a rather dark and clayey marl with low calcium carbonate content (<30%).

The clay minerals (Fig. 3, based on Dupuis et al., 2003), are mainly composed of five types of (mixed-layer) minerals: a mix of illite and mica, kaolinite, chlorite, chlorite–smectite (14c–14s) and illite–smectite (IS R0). Illite–smectite mixed-layer minerals dominate the clay associations throughout the Dababiya H section, except for an interval in the lower CIE/PETM (mainly DQ-bed 2 and 3). In this interval at the top of DQ-bed 1, the chlorite–smectite (14c–14s) mixed layers appear and peak shortly in DQ-bed 2. In this interval the quartz content reaches its highest level. The 14c–14s mixed layers show a good correlation with the lowest smectite percentage in R0 IS (high values of the saddle/I001 curve; Dupuis et al., 2003) recorded in this part of the DQ-bed 2 and in DQ-bed 3 as well. They are also well correlated with the short and abrupt increase of chlorite, kaolinite and illite. From the top of DQ-bed 2 the clay fraction is dominated by the IS R0 mixed layers, which show a relatively variable content of smectite layers ranging between ~65% and ~75% (saddle/001; Dupuis et al., 2003). During the upper CIE quartz contents become low and the clay association is dominated by IS R0 mixed layers and kaolinite is on the average present as ~5% of the clay fraction. The smectite content of the IS R0 mixed layers is relatively high (~80–85%) and it progressively decreases (~65–70%). In the post-CIE interval, a special phenomenon is the increase of the slowly progressive content of kaolinite from 5% to 15% whereas the levels of other clay minerals, such as chlorite and illite, remain low.
2.3. Sample preparation

About 50 g of rock/sediment from each of the 32 studied samples was dried at 60 °C for 24 h. Then, samples were soaked in a 0.5 M Na₂CO₃ solution for a couple of days. After disintegration, the samples were washed over a 63 μm sieve and dried at 60 °C. For some samples, the soaking treatment was repeated because sediment remained aggregated. After drying, the residues were sieved with mesh-sizes of 125 and 630 μm. The benthic foraminiferal assemblages in the fractions of 63–125 and 125–630 μm were studied separately. Wherever possible, at least 200 specimens were counted in both size fractions of each sample. In the case of high test densities, splits were made of at least 200 specimens (excluding non-calcareous agglutinated foraminifera) by using an ASC microsplitter.

2.4. Taxonomy

Most taxa were identified at genus and species level, largely following the taxonomy of Speijer (1994). Over 85 taxa were identified of which about 40 are discussed in more detail. A large group of agglutinated taxa and diverse nodosariids were lumped. Parts of branching agglutinated foraminifera were excluded because a sound
method to count individual specimens lacks. A group of non-calcareous agglutinated taxa (i.e., genera *Trochammina*, *Haplophragmoides*, *Bathysiphon*, etc.) were excluded from all calculations and analyses. The quality of their preservation was very poor, causing determination problems. The distribution data of this group are discussed separately (Section 3.3). Other calcareous taxa were lumped at genus level because of low numbers or owing to the high degree of morphologic variability (e.g., *Nuttallides* spp., *Gyroidinoides* spp., *Pullenia* spp., etc.).

2.5. Quantitative foraminiferal analysis

Benthic foraminifera were counted and studied separately in the 63–125 and 125–630 μm size fractions (Appendix A, part 1 and 2). Results are presented separately for the most abundant taxa in both size fractions and these results are combined as well for the most abundant taxa (63–630 μm, Appendix A part 3). Planktonic foraminifera were counted and studied in the 125–630 μm size fraction (Appendix A, part 4).

Principal component analysis (PCA, Canoco 4.0, GLW-CPRO, Ter Braak and Šmilauer, 1998) was applied to identify relationships between the taxa (63–630 μm) in multivariate space by indirect gradient analysis. Data were log-transformed before analysis.

3. Results

3.1. General faunal and paleoenvironmental indices

General faunal and paleoenvironmental indices are graphically summarized in Fig. 2. The negative excursion of the δ¹³C record marks the CIE interval and since we have no control on the exact termination of the PETM in Dababiya, the CIE interval is taken as reference for all events.

The variation of the number of benthic foraminifera per gram sediment exhibits a very similar pattern in both smaller and larger size fractions (Fig. 2). In the Esna 1 unit, these numbers are constant but at the P/E boundary, a strong decrease is observed. From DQ-bed 1 to the
base of DQ-bed 3 benthic foraminifera are almost absent, except for occasional siliceous agglutinated forms (see Section 3.3) and a few small specimens in DQ-bed 2. In DQ-bed 4 benthic foraminiferal densities increase strongly and in DQ-bed 5 the highest density is observed. Foraminiferal densities remain high, but steadily decrease above the DQ-beds. The Shannon diversity of the total benthic assemblage (63–630 μm) is very stable in the Esna 1 unit. Diversity drops to a minimum directly underneath the P/E boundary and remains low up to DQ-bed 3, but gradually increases again from the base of DQ-bed 4 to reach a maximum at the base of DQ-bed 5. Above the DQ-beds, diversity slightly decreases again. The density of planktic foraminifera exhibits a very similar pattern to that observed in the benthic foraminifera, but planktic foraminiferal densities are generally higher. P/B ratios exhibit average values of about 50% in the Esna 1 unit and increase strongly up to 95% in the upper DQ-beds and decrease again above the DQ-beds.

### 3.2. Benthic foraminifera

Benthic foraminifera were counted and studied separately in the 63–125 and 125–630 μm size fractions (Appendix A). Results are presented separately for the most abundant taxa in both size fractions and these results are combined as well for the most abundant taxa (63–630 μm, Appendix A). The smaller size fraction constitutes at least 70% of the total foraminiferal community (63–630 μm), but in DB-beds 3 and 4 more than 90% of the assemblage is composed of specimens smaller than 125 μm (Fig. 2).

In the lower CIE (DQ-bed 1 to middle DQ-bed 3) only few (calcareous) benthic foraminifera are encountered. In the larger size fraction (125–630 μm) rare specimens (samples at 0.73 and 1.15 m) are identified as reworked upper Paleocene specimens (Angulogavelinella avnim-elechi, Cibicidoides pseudoacutus; see also Appendix A2). Non-calcareous agglutinated taxa are excluded from this part of the results and are discussed separately (Section 3.3).
In the 63–125 μm fraction some taxa are mainly or exclusively encountered in the Paleocene (Esna 1 unit, Fig. 4: C. pseudoacutus, A. avnimelechi, Anomalinoïdes affinis, Sporobulimina eocaena). Other taxa are found quite evenly distributed in both the Paleocene and Eocene samples (Fig. 4: C. rigidus, Bulimina midwayensis, A. cf. midwayensis, C. succedens, Loxostomoides applinae, Neoepionides lunatus, Gyroidinoïdes spp., Osangularia plumeriae, Spiroplectinella dentata/esnaensis). The dominant taxa in this size fraction (Globocassidulina subglobosa and Bulimina cf. thanetensis) are most abundant in the upper Esna 1 unit, although they are also rather abundant in the middle to upper CIE. A small group of taxa dominates the middle CIE (A. aegyptiacus, Lenticulina spp., Stainforthia spp., Valvulineria scrobiculata). A large group of taxa occurs in the Paleocene, but become abundant only in middle/upper CIE beds (DQ-beds 3–5) to post-CIE beds (Valvalabamina depressa, V. planulata, A. zitteli, C. pharaonis/decoratus, Turrilina brevispira) and especially B. callahani, Oridorsalis plummerae, Tappanina selmensis and Uvigerina sp. become very abundant.

Taxa that are abundant and dominant in the smaller size fraction are rarely encountered in the 125–630 μm fraction (Fig. 5). In the Paleocene, C. pseudoacutus is one of the most abundant taxa, and the foraminiferal assemblages are rather constant in composition throughout the Paleocene interval. However, at the P/E boundary a distinct change is observed and Anomalinoïdes cf. midwayensis and Lenticulina spp. briefly dominate. In DQ-beds 3 and 4 Lenticulina spp. is very abundant (>50%) together with A. aegyptiacus, A. zitteli, C. pharaonis/decoratus and V. scrobiculata. From DQ-bed 3 onwards Bulimina callahani becomes progressively more abundant; up to 25% of the total assemblage above DQ-bed 5.

A selection of the twenty-four most abundant taxa for the combined smaller and larger size fraction (Fig. 6)

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Fig. 5. The results of the 125–630 μm fraction: relative distribution patterns of the 36 most common taxa. The grey area marks the interval in which specimens are absent or poorly preserved.
show that small-sized taxa (e.g., *Bulimina cf. thanetensis*, *G. subglobosa*, *Anomaloides aegyptiacus*, *N. lunatus* etc.) are the dominant component when considering the 63–630 μm size fraction.

### 3.3. Non-calcareous agglutinated foraminifera

This taxonomically difficult group mainly consists of *Trochammina* spp., *Haplophragmoides* spp. and *Bathyysiphon* spp. (Plate I, Figs. t, u and v), and specimens are always mechanically compressed and often poorly preserved. Therefore, this group is treated separately from the other taxa. This group is very frequent in the Esna 1 unit (Fig. 7). At the P/E boundary, their density decreases strongly and absolute numbers remain very low, except for two isolated peak occurrences in DQ-beds 3 and 4. Their relative proportion in the total foraminiferal assemblage peaks up to 100% above the P/E boundary (DQ-beds 1–2) and in the lower to middle CIE (DQ-beds 1–4). However, these peaks are explained by the near or total absence of calcareous foraminifera and not by high absolute densities. Relative frequencies are much lower or minimal in the late Paleocene and middle to post-CIE (DQ-bed 4 and younger).

### 3.4. Planktic foraminifera

Planktic foraminifera were identified at generic level (>125 μm, Fig. 8, Appendix A). The assemblage is mainly composed of *Acarinina*, *Morozovella* and *Subbotina*, which together make up >85% of the total planktic assemblage in the upper Paleocene (Esna 1). *Subbotina* reaches >30%, *Morozovella* is the dominant surface-dweller taxon (up to 40%), whereas *Acarinina* does not reach percentages above 20%. Frequencies of *Igorina*, *Parasubbotina* and *Globanomalina* are generally less than 5%, *Chiloguembelina* and *Zeauvigerina* occur only rarely (<1%).

In the lower CIE (DQ-bed 1 to middle DQ-bed 3) planktic foraminifera are absent, except for a peak in relative abundance (but not in absolute abundance, see Fig. 2) of poorly preserved *Acarinina* in the lower part of DQ-bed 2, in which a multichambered variety of the flat-spired *Acarinina sibaiyaensis* is the main component. Within this peak interval, *Morozovella* is almost absent. *A. sibaiyaensis* and *A. africana* also occur, but in low numbers. In the middle CIE (top DQ-bed 3) *Acarinina* is still the dominant taxon, except in the sample at 1.55 m where it decreases and *Parasubbotina* and *Subbotina* briefly increase. During the middle CIE
Morozovella starts to recover and in the interval between 1.68 m to 1.93 m *M. allisonensis* is recorded infrequently. In the upper CIE the planktic foraminiferal assemblages are more diversified; *Acarinina* gradually decreases and *Morozovella* and *Subbotina* increase. *Acarinina multicamerata* and *M. allisonensis* are absent from this interval onwards. In the post-CIE (above DQ-bed 5) planktic foraminiferal assemblages continue to diversify.

### 3.5. Other observations

In the upper Paleocene Esna 1 beds high densities of pyritized burrows (diameter < 1 mm) are encountered in the sample residues. Also above the P/E boundary in the lower CIE/PETM (DQ-beds 1–2), many pyritized burrows are present in combination with high numbers of fossilized parts of fishes (e.g., bones, teeth, jaws, scales) and phosphate nodules. Fine white veins of secondary gypsum and anhydrite parallel to the sediment layering are found in the lower to middle CIE (throughout DQ-bed 3). In the middle CIE (DQ-bed 3), the number of fish remains decreases and in the upper CIE (DQ-bed 4) they become rare or absent.

### 3.6. Principal components analysis of the benthic foraminiferal data

A principal components analysis (PCA) was performed on the 63–630 μm size fraction (Fig. 9). The PCA-analysis offers a good method to summarize graphically the faunal patterns of 85 species in 23 samples in two dimensions. The five taxa loading most positively or negatively in each analysis are listed in Fig. 9. Appendix B presents all scores of taxa samples for the analysis of the combined (63–630 μm) data set. The first two PCA-axes explain 63% (1st axis 39.0%, 2nd axis 23.9%) of the variance from the higher assemblages.

The PCA points at a subdivision of the Dababiya H subsection in four intervals: 1) the upper Paleocene (Esna 1), 2) lower CIE (DQ-bed 1 to middle DQ-bed 3), 3) middle CIE (middle DQ-bed 3 to top DQ-bed 4) and 4) upper to post-CIE (DQ-bed 5 and younger Esna 2. The paleoecological interpretation of these intervals is discussed in consecutive sections in the discussion.

### 4. Discussion

#### 4.1. Introduction and previous studies

The Dababiya H section is one of the most expanded and relatively continuous sections encompassing the CIE identified so far (Dupuis et al., 2003). It contains important information on the sequence of events in the Southern Tethys during this interval, which is partly missing in other marine sections in the region and other areas of the world (e.g., Thomas, 1998; Ouda, 2003). The Dababiya record provides a more complete picture of the biotic and paleoenvironmental development of the Nile basin, particularly during the early stages of the CIE. Furthermore, benthic foraminifera in the size fraction 63–125 μm showed to yield important information on, for instance, repopulation events during which foraminifera attained only small test sizes.

For the middle to upper CIE in the southern Tethys, very similar faunal and paleoenvironmental patterns have been identified at the nearby Aweina and Qreiya sections (Speijer and Schmitz, 1998; Speijer et al., 2000; Speijer and Wagner, 2002; Knox et al., 2003; Soliman, 2003). At outer neritic depths a major turnover took place from a pre-extinction *A. avnimelechi*-dominated assemblage to a long-term post-PETM assemblage dominated by *B. callahani* (Speijer and Wagner, 2002). At a number of neritic to upper bathyal sites (paleodepth 75–500 m) the assemblage immediately following the extinction level is composed of only a few taxa like *A. aegyptiacus, Valvulineria* spp. and *Stainforthia* spp. (Speijer and Wagner, 2002). This low-diversity and high-dominance fauna is interpreted as being representative of a heavily disturbed environment.
Fig. 7. Distribution data of the group of non-calcareous agglutinated taxa (63–630 μm). The relative proportion of this group as part of the total number of foraminifera is compared with the actual number of specimens per gram of sediment.

Fig. 8. Planktic foraminiferal data: the relative distribution patterns are shown for the 6 most abundant genera. The grey area marks the interval without or poorly preserved specimens.
in which highly eutrophic conditions and nearly permanent anoxia prevailed.

Previous semi-quantitative investigations of the benthic foraminiferal record of Dababiya in Dupuis et al. (2003) showed assemblages with predominantly thick-walled and robust specimens, which may have been an artifact of sample preparation, differing from the methods used here. Alegret et al. (2005) have also quantitatively studied the benthic foraminiferal record in the same interval of the Dababiya section, largely based on the same sample set (collected by C. Dupuis and others). However, in various aspects our foraminiferal data and interpretations differ significantly from Alegret et al. (2005). These differences concern taxonomic, quantitative, and taphonomic discrepancies.

The taxonomic concepts used by Alegret et al. (2005) differ significantly from previous works in Egypt (e.g., LeRoy, 1953; Luger, 1985; Speijer, 1994). Some taxa that appear in Alegret et al. (2005) have not been described previously in this area (e.g., Anomalinoides ammonoides, A. acutus, Valvalabamina lenticula) or seem to have been erratically identified (e.g., judging from the distribution patterns their A. aegyptiacus is probably a species that we consider as A. affinis or A. cf. midwayensis). To illustrate this and for comparison with other studies the important taxa in our study are displayed in the appendices (Plates I and II; note that Alegret et al. (2005) provide no taxonomic information).

More important is the fact that certain abundance patterns, particularly those of small-sized species such as G. subglobosa, B. callahani, B. cf. thanetensis, are
totally different from the patterns in our study. Small taxa, such as *Bulimina* cf. *thanetensis*, *A. aegyptiacus* and *G. subglobosa*, are the dominant taxa in our material of the 63–630 μm size fraction. This is not surprising, since in well-preserved foraminiferal assemblages smaller taxa are usually ubiquitous. However, in the dataset of Alegret et al. (2005), which is also based on the fraction >63 μm, small-sized taxa are quite uncommon: *G. subglobosa* occurs consistently, but always well below 5% of the total assemblage, whereas *Bulimina* cf. *thanetensis* is not recorded at all. Possibly the latter species has been recorded under a different name, but Alegret et al. (2005) mention no other buliminid occurring consistently in large numbers in the lower and middle part of the studied section. The same discrepancy can be observed in the frequencies of many other small small species such as *B. callahani*, *B. farafranensis*, *T. selmensis*, and *T. brevispira*). By contrast, the most common calcareous taxa in the data set of Alegret et al. (2005) are large taxa such as *Lenticulina* spp., *Cibicidoides* spp., and *Anomalinoideas* spp. just like in our partial dataset of the fraction >125 μm. It thus appears that their data set is consistently skewed towards larger and more robust taxa, just like the residues documented semi-quantitatively by Dupuis et al. (2003). Consequently, we are convinced that the data of Alegret et al. (2005) do not reflect the original content of the fraction >63 μm, the reason of which we can only speculate on. Possibly for the same reason Alegret et al. (2005) also failed to (fully) identify the pioneering assemblage that occurs from the top of DQ-bed 2 and in higher densities in DQ-bed 3 and we further encountered benthic foraminifera in samples (0.73 and 1.15 m) in the interval described as barren by Alegret et al. (2005). Consequently, also our interpretations differ significantly. For instance, the decrease of infaunal/endobenthic morphogroups in the early CIE (Alegret et al., 2005) is in our opinion not explained by oligotrophy. All lithological and faunal parameters in our study indicate the opposite: severe dys- to anoxic conditions, followed later in the early CIE by very high organic matter fluxes related to upwelling (see Section 4.3). Evidence for highly eutrophic and anoxicic conditions is also observed in other localities in Egypt (Speijer and Wagner, 2002). In our view, also the significance of the apparent acme of non-calcareous agglutinated taxa (e.g. *Trochammina*, *Haplophragmoides*, *Bathysiphon*) in the early CIE is overestimated by Alegret et al. (2005). Our data (Fig. 7) clearly show that the high relative abundance of these taxa only derives from their preferential preservation relative to the calcareous taxa resulting from calcite dissolution. A potentially useful evaluation of relative abundance variations of these agglutinated taxa can only be made on a calcite free basis, i.e. by disregarding or dissolving the calcareous taxa in all samples. In order to reduce taphonomic effects from dissolution, we omitted the non-calcareous agglutinated taxa from our main quantitative analyses.

In the following, we will present a different and more comprehensive interpretation of the paleoenvironmental development in Dababiya across the Paleocene/Eocene boundary. We use recent advances in modern foraminiferal ecological research to explain some of the observed fossil foraminiferal patterns at Dababiya, which we additionally use for discussing a hypothesized mechanism behind the global BEE.

### 4.2. Late Paleocene

The upper Paleocene pre-extinction fauna in Dababiya is mainly composed of taxa characteristic of outer neritic conditions in the Southern Tethys (e.g., Speijer, 1994). Some bathyal taxa (e.g., *Gavelinella beccariformis* and *Pullenia coryelli*) are encountered in (very) low densities and are markers for the pre-extinction faunas as they disappear globally in the lowermost Eocene (Speijer et al., 1995). The scattered occurrence of bathyal taxa points at deposition at a depth of ~175–200 m, similar to the nearby Gebel Aweina succession (Speijer and Schmitz, 1998). This paleodepth is slightly deeper than estimated previously based on a preliminary benthic foraminiferal data set presented by Dupuis et al. (2003), in which bathyal taxa appeared completely absent. The pre-extinction fauna is dominated by *G. subglobosa*, *Bulimina* cf. *thanetensis*, *Cibicidoides* spp.
and A. affinis. The assemblage is named after the commonly present marker taxon A. avinimelechi, which occurs extensively in Paleocene outer neritic and upper bathyal deposits of the southern Tethys (Aubert and Berggren, 1976; Speijer et al., 1995). General characteristics of the pre-extinction fauna are a high diversity in all size fractions and very high densities of smaller taxa. The high numbers of small Bulimina cf. thanetensis and G. subglobosa indicate mesotrophic conditions with (seasonally) fluctuating oxygen and productivity levels, similar to modern outer shelf to deep-sea assemblages (e.g., Gooday and Turley, 1990).

In addition, the non-calcareous agglutinated taxa (including Haplophragmoides spp.) point at (seasonally fluctuating) low-oxygen conditions and variable food levels as well (Kuhnt et al., 1996).

In the topmost centimeters of the Paleocene, diversity and foraminiferal densities drop rapidly and the poor preservation of foraminiferal tests, e.g., dominance of thick-walled taxa such as Lenticulina spp. and Anomalalinoides cf. midwayensis attest that these reductions result from increased CaCO3-dissolution. This dissolution is likely the result of the anoxic bottom water conditions and high organic matter load that existed later during the early stages of the CIE/PETM, comparable with the “burning down” of Mediterranean sapropel beds (Diester-Haass et al., 1998).

The illite–smectite mixed layer (IS R0), which dominates the clay mineral association, is currently interpreted as indicating warm and prevailing arid conditions with seasonally fluctuating (humidity) levels (Gibson et al., 2000), which is in line with low kaolinite levels. This seasonal signature could be responsible for seasonal changes in the ventilation of the water column and the fluctuations in productivity and ventilation in the basin, as inferred from the foraminiferal faunas and the presence of (pyritized) burrows in this interval.

### 4.3. Lower CIE/PETM

Above the P/E boundary, a non-calcareous laminated clay is deposited, characteristic of anoxic environments where no bottom fauna is present (e.g., Wignall, 1994). The anoxic conditions prohibited organisms to live in the benthic realm during this period explaining the absence of foraminiferal tests. Postmortem dissolution of carbonate cannot be the only cause for the disappearance of calcareous taxa because non-calcareous agglutinated taxa also disappeared.

A relative sea-level record for the basin indicates that latest Paleocene deposition occurred during a late sea-level high stand (HST), which was followed by a sea-level rise (TST) during the early CIE (Speijer and Wagner, 2002). This sea-level curve was derived from observed unconformities, channel incisions, and foraminiferal and ostracode data. At Dababiya a distinct channel-like incision underlies the Dababiya Quarry beds which wedge out on outcrop scale (Dupuis et al., 2003). This is in line with the proposed sea-level record for the region (Speijer and Wagner, 2002). Consequently, the GSSP for the P/E boundary is situated at an unconformity without low stand (LST) deposits, which is also supported by the sudden 1–1.5‰ δ13Corg negative shift at the base of DQ-bed 1.

The basal Eocene beds reflect deposition during the next sea-level rise (TST), disrupting basin circulation and leading to stratification of bottom waters. Faunal records from other successions in the basin suggest a sea-level rise of ~20 m from the onset of the CIE to deposition of the calcarenitic bed (=DQ-bed 5) (Speijer and Morsi, 2002; Speijer and Wagner, 2002).

The sedimentological composition of DQ-bed 1 and 2 reveals the reworking of progressively more distant environments as the sea encroached and eroded coastal plain deposits. In the lower CIE (DQ-bed 1) the clay almost certainly originates from the superficial horizons of smectitic soils and/or smectite–chlorite (14c–14s) bearing sediments of coastal lagoons and lakes in fairly flat and poorly drained landscapes. The increase of quartz (top DQ-bed 1 to base DQ-bed 2) may correspond to material from a more distant or at least different area: a fresh crystalline basement as suggested by the chlorite (very sensitive to weathering) but also partly derived from previously weathered material (14c–14s mixed layers and kaolinite).

At the transition from DQ-bed 1 to 2 the basin circulation changed and upwelling initiated or increased. Higher TOC levels and the occurrence of phosphatic concretions and fish remains support the occurrence of (intense) upwelling (Parrish and Curtis, 1982). Other localities in Egypt indicate upwelling of mid-depth Tethyan waters into the Nile Basin (Speijer et al., 1996; Schmitz et al., 1997; Speijer and Wagner, 2002). Our study shows that this period of upwelling extended to the middle CIE (DQ-bed 3), whereas former studies placed it in the lower CIE. The start and increase of upwelling of nutrient-rich deep water may be explained by stronger NE trade winds as a result of increasing atmospheric contrast between the coastal zone (arid, sub-tropical) and the continent (humid, tropical), causing intensified off-shore directed Ekman transport (Speijer et al., 1996; Speijer and Wagner, 2002). This circulation pattern fits in a broader view of
the Tethys during the early Eocene: climate modeling indicated/suggested formation of high-saline deep water in the northern Tethyan realm by high evaporation rates (Huber and Sloan, 2001).

An important temporary and synchronous high peak of kaolinite, chlorite, illite and 14c–14s mixed layers marks the final stages of the lower CIE (DQ-bed 2). This complex mix of clay minerals originates from different parts of the upstream catchment area and appears to be linked to an erosion wave triggered upstream on the continent by the late Paleocene sea-level fall (Dupuis, 2000) and the climate change in the early Eocene. The rise in mixed clay minerals suggests augmented continental runoff as a result of increased continental precipitation and erosion, caused by very warm and perennially humid conditions. Additionally, the higher detrital influx at Dababiya during this transgressive phase in the lower CIE was enhanced by the closer position of the shoreline.

Increased terrestrial organic matter (i.e., fossilized wood) identified in this interval (Dupuis et al., 2003) supports an increase in continental runoff and may have enhanced the productivity associated with the upwelling in the shallower zones of the basin. Shallow-dwelling planktic foraminifera (>90% Acarinina) have been preserved in a level at the base of DQ-bed 2. Acarinina is generally regarded as being indicative of oligotrophic conditions (Pearson et al., 1993; Norris, 1996), but here the dominant taxon is a multi-chambered variety of A. sibaiyaensis, which we consider to have flourished under nutrient-rich conditions.

Although basin circulation conditions clearly changed during the lower CIE, the seafloor remained inhabitable for benthic faunas because of long-term or frequently occurring anoxic conditions. High organic fluxes to the seafloor, facilitated by upwelling, led to high oxygen consumption rates depleting the benthic environment of oxygen. In this type of environment, calcium carbonate tests arriving from other parts of the basin or from surface waters (e.g., plankton tests) would have dissolved by metabolic release of CO2 (e.g., Emerson and Archer, 1990). CaCO3 corrosiveness by the destabilization of gas hydrates as a cause of the absence of calcareous specimens in this interval, as proposed by Alegret et al. (2005), is not very likely at these shallow depths (Zachos et al., 2005). Occasionally, the seafloor was briefly re-oxygenated during deposition of DQ-bed 2, as shown by the presence of very low numbers of small (<125 μm) pioneering taxa (A. aegyptiacus assemblage). These periods, however, did not last long enough to sustain foraminiferal faunas or other benthic organisms on the long term.

4.4. Middle CIE

During the middle CIE conditions at the seafloor improved somewhat, enabling pioneering low-diversity benthic assemblages to occasionally inhabit the seafloor (A. aegyptiacus assemblage). This low-diversity assemblage is indicative of stressful conditions with low-oxygen levels and high productivity (Speijer and Wagner, 2002). The low foraminiferal densities in the middle CIE indicate that the poorly oxygenated conditions lasted almost continuously or occurred at a high frequency throughout this interval and repopulation by the A. aegyptiacus assemblage occurred only during very ephemeral events. Modern analogues of such foraminiferal communities are for instance observed in oxygen minimum zones (e.g., Arabian Sea, Den Dulk et al., 2000), semi-permanent anoxic basins (e.g., Santa Barbara Basin, Bernhard and Reimers, 1991) and shelf margins with river-induced anoxia (Van der Zwaan and Jorissen, 1991). In the latter areas, specialized taxa inhabit the (highly) eutrophic estuarine environments and some are able to survive anoxic periods of more than two months, (Moodley et al., 1997; Duijnstee et al., 2004; Ernst et al., 2005). General characteristics of low-oxygen stress-assemblages are relatively small, thin-walled, sometimes highly porous taxa and low diversity (Bernhard and Sen Gupta, 1999). The community turnover during the CIE at Dababiya also resembles patterns of foraminiferal communities that thrived in frequently disturbed environments (low oxygen/high organic flux), such as sapropel successions (Jorissen, 1999).

Certain foraminifera have the ability to exploit different metabolic pathways when chemical conditions change in their environment. For instance, symbiotic relationship(s) with other organisms such as bacteria (or diatom chloroplasts) supply energy, which enables foraminifera to thrive in anoxic environments (Bernhard, 2003). Thomas (2003) suggested special metabolic adaptations of surviving taxa (chemosymbiotic bacteria) as an explanation for the changed trophic conditions associated with a decoupling of the benthopelagic system in the deep-sea. This, however, does not explain the faunal developments in shallower continental basins. Here, perhaps certain foraminifera profited from their capacity to adapt their life-style to the environment: recent foraminifera in heavily perturbed environments have shown to switch between different life-strategies (habitat shifts, population dynamics), which enables them to cope with repetitive environmental disturbances, an edge they have over equilibrium species (Duijnstee et al., 2004; Ernst et al., 2005). For
example, some taxa living in such environments are opportunists: capable of responding immediately to favorable conditions by changing reproduction and adult survival rates, whereas other taxa are stress-resistant, capable of surviving (relatively) extreme environmental conditions with low reproductive rates. Here, the opportunistic taxa are represented by *A. aegyptiacus, Valulineria* spp., *Stainforthia* spp., *Bulimina farafraensis* and *Lenticulina* spp. Stress-resistant are for instance *Bulimina* cf. *thanetensis* and, to a somewhat lesser degree, *G. subglobosa*, which in this phase appear relatively abundant in the small-sized fraction. The quality of preservation of the tests and the absence of the larger “Paleocene” taxa indicate that reworking is not responsible for their occurrence in this interval. In addition, the peaks in non-calcareous agglutinated foraminifera (among them high densities of *Haplophragmoides* spp.) observed in this interval are related to the low-oxygen and variable organic flux conditions (e.g., Kuhnt et al., 1996).

Shallow-dwelling taxa of the planktic foraminiferal genera *Acarinina* and *Morozovella* dominate in this interval. At the top of DQ-bed 4 the diversity and the density of both benthic and planktic foraminifera augmented strongly. The long-term or highly frequent extreme eutrophic conditions that ruled from the lower CIE onwards disappeared and basin ventilation increased with lower organic matter fluxes. The regular decrease of quartz content in the middle CIE indicates decreasing erosion accompanying the sea-level rise and coincides with the maximum reworking of continental organic matter and with the onset of the restoration of the calcite productivity and preservation. A moderate atmospheric contrast between the coastal zone and the continent could have abated upwelling intensity by reducing trade wind strength. The return of IS mixed layer, and (traces of) illite, chlorite and kaolinite in the clay mineral associations corresponds to the restoration of warm and increasingly arid (seasonally fluctuating) conditions, as prevailed in the late Paleocene.

### 4.5. Upper to post-CIE

In the upper CIE, the diversity and density of both planktic and benthic foraminifera reached very high levels. The conditions were very favorable for the productivity of foraminifera with sufficient nutrients and without limiting oxygen levels. Deep-dwelling planktic foraminifera became more abundant because of improved basin circulation. The basin-wide distribution of DQ-bed 5 or its equivalent known as the calcarenitic bed (Schmitz et al., 1997) corresponds to a maximum flooding surface (msf) resulting from reaching the highest relative sea-level during the P/E transition (Speijer and Wagner, 2002). Illite/Smectite R0 mixed layers dominate the late CIE clay mineral association and the progressively decreasing smectite content may indicate higher sedimentation rates. In the post-CIE a special phenomenon is the increasingly rising kaolinite content (15% to more than 50% higher up in the Esna 2, Dupuis et al., 2003), without any correlation with the other clay minerals (e.g., chlorite and illite). This progressive long-term increase of kaolinite appears very different compared to the short high discharge of detrital clay minerals in the lower CIE (DQ-bed 2) and must relate to the weathering evolution of the region during the climatic optimum.

The post-CIE interval is dominated by *B. callahani*, an indication that low oxygen/high productivity stress increased: a development comparable to other continental margin sites in the world with buliminid-dominated faunas (Ortiz, 1995; Thomas, 1998). Overall, benthic faunas reflect mesotrophic conditions with seasonal variation in oxygen and food levels, resembling pre-extinction conditions in the late Paleocene. The planktic assemblage consists of more deep-dwelling genera indicating increased exchange of bottom and surface waters.

### 5. Conclusions

The paleoenvironmental developments at Dababiya during the late Paleocene to early Eocene are interpreted by combining various paleoenvironmental indicators (Fig. 10). The Dababiya H section is one of the thickest successions covering the CIE/PETM interval identified so far, which has enabled us to study the paleoenvironmental development and biotic responses in higher detail compared to other sections in the southern Tethyan region.

During the late Paleocene warm and arid conditions prevailed. Seasonally fluctuating mesotrophic conditions changed into extreme eutrophy and anoxic conditions during the early CIE/PETM as a net result of increased temperature and disruption of the circulation in the basin. On the continent, the climate changed and conditions became warm and humid throughout the year.

During prolonged intervals of the early to middle CIE the neritic environment suffered from long-term or highly frequent oxygen depletion, rendering living conditions for benthic organisms difficult in or at the sea floor. At the end of the lower CIE stratification ended and upwelling started or initiated with high...
Fig. 10. Summary of all the paleoenvironmental indicators in this study and the interpreted paleoenvironmental reconstructions. See text for discussion.
organic fluxes. In the middle CIE, occasionally improved oxygenation enabled pioneering opportunistic small benthic foraminiferal faunas to thrive for brief periods. For both the benthic and planktic foraminiferal faunas conditions improved during the late CIE. The strong increase in diversity and foraminiferal densities marks a return to seasonally fluctuating ventilation and productivity conditions, comparable to the upper Paleocene situation. The clay mineralogy suggests increased seasonal climatic variability on the continent with overall more arid conditions. The buliminid-dominated post-CIE period again hints at a periodic reduction of oxygen levels and increase of organic matter load of the benthic environment.

The foraminiferal taxa surviving and dominating the CIE/PETM interval and post-PETM may have had a special adaptation or capacity to cope with the environmental change. It remains difficult to explain why taxa with wide geographical and bathymetric ranges become extinct at the P/E boundary. Various severe and global perturbations (e.g., warming of the ocean’s deep water, CaCO$_3$ corrosiveness, low-oxygen levels, severe eutrophication) of deep and shallow marine environments took place in an exceptionally short period of several thousands of years. We pose that this combination of various types of environmental change, acting on temporarily and geographically different scales, resulted in the global benthic extinction event, instead of a single explanation for the BEE. Since conditions deteriorated for benthic organisms in both deep and shallow environments, an escape from frequently occurring hostile conditions could have been difficult for equilibrium taxa that need a stable environment. Opportunistic stress-tolerant genera or taxa (e.g., *Bulimina* spp., *N. truempyi* and *T. selmensis*) were able to survive the geographically and temporally shifting hostile conditions by surviving in areas that were less affected by environmental disturbances or by a tolerance to a wide range of environmental conditions. Their survival and good capacity to (re)colonize and disperse enabled them to dominate the areas after the environmental perturbations.

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**Appendix A**

1) Census data of the benthic foraminifera in the 63–125 μm fraction.
2) Census data of the benthic foraminifera in the 125–630 μm fraction.
3) Relative frequency of the benthic foraminifera in the 63–630 μm fraction.
4) Census data of planktic foraminifera larger than 125 μm.

**Appendix B**

Species and sample scores for the first two axes of the Principal Components Analysis of the 63–630 μm fraction.

**Appendix C. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.mar micr.2006.03.002.

**References**


