EARLY PALEOGENE ENVIRONMENTAL TURNOVER IN THE SOUTHERN TETHYS AS RECORDED BY FORAMINIFERAL AND ORGANIC-WALLED DINOF Lagellate CYSTS ASSEMBLAGES

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## Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Chapter I: Introduction and Summary</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Chapter II: Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, Tunisia).</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Chapter III: Paleoenvironmental change at the Danian-Selandian transition in Tunisia: planktic foraminifera and organic-walled dinoflagellate cysts records.</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Chapter IV: Transient biotic change within the Danian-Selandian transition in Egypt and Jordan</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Chapter V: The Paleocene-Eocene thermal maximum in Egypt and Jordan: an overview of the planktic foraminiferal record</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>Chapter VI: The impact of Paleocene-Eocene thermal maximum on foraminifera in the southern Tethys (Dababiya, Egypt)</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Chapter VII: Synthesis</td>
<td>181</td>
<td></td>
</tr>
<tr>
<td>Appendix</td>
<td></td>
<td>193</td>
</tr>
</tbody>
</table>
PREFACE

The results of my research are compiled in different papers. My own contributions are as followed:

1) **Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, Tunisia)**, chapter II.
Authors: Elisa Guasti, Tanja J. Kouwenhoven, Henk Brinkhuis and Robert P. Speijer.
Journal: Marine Micropaleontology (2005) 55, 1-17
Status: published.
Own contributions: organic dinocysts evaluation (relative abundances, protoperidinioid/gonyaulacoid ratio and terrestrial/marine ratio); integration of these data with published results on benthic foraminifera, text and figures.

2) **Paleoenvironmental change at the Danian-Selandian transition in Tunisia: planktic foraminifera and organic-walled dinoflagellate cysts records**, chapter III
Authors: Elisa Guasti, Robert P. Speijer, Henk Brinkhuis, Jan Smit and Etienne Steurbaut.
Status: will be submitted to Marine Micropaleontology
Own contribution: collecting samples, stratigraphy of the localities, biostratigraphy, evaluation of planktic foraminiferal assemblages and relative proxies (relative abundances, planktic/benthic ratio, numbers of foraminifera per gram), organic dinocysts assemblages and relative proxies (protoperidinioid/gonyaulacoid ratio, terrestrial/marine ratio), stable isotope measurements (part of them); text and figures.

3) **Transient biotic change within the Danian- Selandian transition in Egypt and Jordan**, chapter IV.
Authors: Elisa Guasti, Robert P. Speijer, Eliana Fornaciari, Birger Schmitz, Dick Kroon and Ahmed Gharaibeh.
Journal: Journal of Foraminiferal Research
Status: submitted
Own contribution: collecting samples in Jordan, biostratigraphy, evaluation of planktic foraminifera assemblages and relative proxies (relative abundances, planktic/benthic ratio, numbers of foraminifera per gram), qualitative analysis of benthic foraminifera of Jordanian samples, part of the stable isotope measurement; text and figures.
4) **The Paleocene-Eocene thermal maximum in Egypt and Jordan: an overview of the planktic foraminiferal record**, chapter V.
Authors: Elisa Guasti and Robert P. Speijer
Journal: GSA special publication "Large Ecosystem Perturbations: Causes and Consequences"
Status: Submitted
Own contribution: collecting samples in Jordan and at Dababiya (Egypt), biostratigraphy, stratigraphy of the localities, evaluation of planktic foraminiferal assemblages and respective proxies (relative abundances, planktic/benthic ratio, numbers of foraminifera per gram); text and figures.

5) **The impact of Paleocene Eocene thermal maximum on foraminifera in the southern Tethys (Dababiya, Egypt)**, chapter VI.
Authors: Sander Ernst, Elisa Guasti, Christian Dupuis and Robert P. Speijer
Journal: Marine Micropaleontology
Status: will be submitted
Own contribution: collecting part of the sample and analysis of planktic foraminiferal assemblages.
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CHAPTER I

Introduction
CHAPTER I

Introduction and Summary

1 Europrox

This project is part of the European Graduate College “Proxies in Earth History”, which aims to understand biological and physical processes and their impact on climatic and environmental changes in the marine record, by multi-proxy approach and compare modern environment with the fossils record. In particular, our research benefits from the exchange between Bremen University and Dutch Universities (Utrecht and Amsterdam), enabling considerable scientific knowledge by training and research embedded in an international environment. Additionally, the cooperative efforts have been expanded beyond the Europrox framework to scientists from other European universities (KU Leuven, Belgium, University of Padua, Italy and University of Lund, Sweden). This network has successfully improved the scientific quality of this research.

2 Objectives of the project

Since the Earth is experiencing major climatic change, probably related to the anthropogenic input of CO₂ into the atmospheric-oceanic system (ICPP, Report 2001), there is increasing research on climatic variation in the geological record. In particular, significant interest is given to the mechanisms involved and to the response of the Earth system during globally warm periods such as the early Paleogene.

Within this perspective, we investigate the response of the marine system to warming events on the continental margin of the Southern Tethys. Like a natural experiment, the Earth experienced a rapid greenhouse event at the Paleocene/Eocene boundary ~55 Ma, known as the Paleocene-Eocene thermal maximum (Zachos et al., 1993). We portray how the marine system reacted to this event and explore a possible hyperthermal event during the middle Paleocene, across the Danian-Selandian transition.

Considering multi-proxy observations, climatic and environmental changes across these intervals of biotic turnover are investigated, unravelling possible similarities between these two events.

Whilst ocean drilling has provided new insights into the characteristics of Paleogene oceans, little is still known on ancient continental margins. For this reason, micropaleontological assemblages from transects in Egypt, Jordan and Tunisia are studied.

In order to extract paleoenvironmental information from the geological records, different biotic proxies from the surface water (organic dinocysts and planktic foraminifera) and from
the sea floor (benthic foraminifera) are integrated. By combining such different datasets, we aim to document more accurately the paleoenvironmental evolution of the area, with emphasis on paleobathymetric and paleoproductivity variations.

In Tunisia, the planktic foraminiferal assemblages are compared with the organic-walled dinoflagellate cysts, in order to improve and refine their use. Whereas Tunisian outcrops provide well-preserved foraminiferal and palynological material, deep weathering caused a nearly complete degradation of organic matter in the Middle East outcrops. Hence, a comparison between foraminifera and organic dinocysts is prevented in Egypt and Jordan. Additionally, profiles spanning good records across the PETM in Tunisia were not found; therefore this event was investigated only in the Middle East.

3 Early Paleogene

The Paleogene (65 to 23 Ma) is well documented as a highly dynamic period, in which the Earth experienced main climatic variations from a warm “greenhouse” to a cooler “Icehouse” world through extreme transient climatic events (Zachos et al., 2001). During this transition, the Paleocene (65 to ~55 Ma) represents a period of significant perturbations and punctuated biotic changes limited by two important events in the Earth history: initiated by the Cretaceous/Paleogene extinction at the base, and culminated in the Paleocene/Eocene thermal maximum. After the perturbation at the K/P boundary, the middle Paleocene (~59 Ma) represented the start of a warming phase, which culminated in a hyperthermal event known as the Paleocene/Eocene thermal maximum (~55 Ma).

During the early Paleogene, the Earth was generally much warmer than today. The polar region was free of ice sheets, palm trees grew at 60°N, crocodiles were swimming at 75°N and subtropical conditions prevailed in parts of Antarctica. Additionally, pelagic organisms were marked by several diversification pulses and the carbon isotopic record suggests long-term recovery of the global carbon cycle after the perturbation at the Cretaceous/Paleogene boundary, leading to a \( \delta^{13}C \) maximum during the late Paleocene (Shackleton, 1986; Corfield, 1994).

According to Kennett and Stott (1990), the Tethys was the source of warm deep-water formation (Warm Saline Deep Water: WSDW). Additionally, Bice (2000) suggested that WSDW could have co-existed with cooler high latitude sourced water masses. WSDW may have dominated at intermediate ocean depths in the Atlantic and Indian sector Southern ocean, while a cooler source with a small WSDW component dominated in the North Atlantic. Still, recent modelling studies (e.g. Huber et al., 2003) indicate that deep convection of warm saline water occurred in the Northern Hemisphere, whereas the Southern ocean was relatively fresh and surface temperatures were cooler.

During the Paleocene, sea level was generally high, although interrupted by some short-term fluctuations (Haq et al., 1987). The upper Paleocene-lower Eocene was marked by a major transgressive phase related to the opening of the Atlantic Ocean (Reykjanus) and the failed
rifting of the North Sea (Hardenbol et al., 1998). Superimposed on this general trend, several third order sea-level cycles are identified (Hardenbol et al., 1998).

3.1 Paleocene-Eocene thermal maximum
At the base of the Eocene (~55 Ma), superimposed to the general warming trend, an abrupt short extreme warm period developed (Zachos et al., 1993), identified as the Paleocene-Eocene thermal maximum (PETM) (Fig. 1) or Initial Eocene thermal maximum (IETM). This global perturbation of the biosphere is expressed in major faunal turnover and a negative carbonate isotopic excursion (CIE). The most severe extinction event in benthic foraminifera of the last 90 Ma (Tjalsma and Lohmann, 1983) took place simultaneously with a diversification in the surface waters (Kelly et al., 1996; Crouch et al., 2001). A sharp 2-3‰ negative carbon isotopic excursion (CIE) in marine and terrestrial carbonate (Kennett and Stott, 1991; Koch et al., 1995) is associated with this event. During this brief interval, the temperature of the deep ocean and high latitude surface waters were ~6-8°C warmer (Kennett and Stott, 1991; Bralower, 2002).

The most widely accepted idea is that initial deep-sea warming led to a massive dissociation of oceanic methane hydrates, leading to further warming (Dickens et al., 1995). Other theories involve an increase of volcanic emission (Eldholm and Thomas, 1993) or a comet impact (Kent et al., 2003). A new alternative theory proposes intrusion of mantle-derived melts into carbon-rich sediments in the northeast Atlantic as cause for an explosive release of methane (Svenses et al., 2004).

Fig. 1 Lithological sketch, time scale and main events in the studied area during the early Paleogene
Most probably, the PETM was not a unique event, but the most dramatic one of a series of brief warm periods known as hyperthermals in the late Paleocene to early Eocene (Thomas and Zachos, 2000).

Moreover, the global perturbation of the carbon cycle suggest similarities with present-day anthropogenic carbon input (Dickens, 1999); hence a significant attention is given to this event, as a natural experiment to investigate the Earth’s mechanisms in response to a high input of CO$_2$ in the ocean-atmosphere system.

The studied area (Egypt and Jordan) records major turnover in planktic foraminiferal assemblages, associated with the benthic foraminiferal extinction and the CIE-interval, comparable with the global record.

### 3.2 Middle Paleocene

Compared to studies focusing on the PETM, little has been carried out on the Danian-Selandian transition. This period is significant for the evolution of Paleogene planktic foraminifera, as indicated by increasing species diversity and diversification, mainly in the occurrence of taxa with a muricate wall texture (morozovellids, acarininids, igorinids) (Kelly et al., 1996; Norris, 1996). Moreover, the end of the Danian is marked by an increase in depth stratification of planktic foraminifera (Quillévéré and Norris, 2003), and the simultaneous acquisition of photosymbiotic algae within muricate taxa could represent an evolutionary novelty within planktic foraminifera as a trophic strategy to thrive in oligotrophic environments (D’Hondt et al., 1994; Norris, 1996).

Several studies in the Tethys area portray biotic and geochemical variation in several localities within the Danian-Selandian transition (Fig. 1). In the Middle East, this transition is marked by black shale bed rich in organic carbon and fish remains, strongly dominated by anomalous foraminiferal assemblages (Speijer, 2003), and defined as “Neo-duwi event”. We expand on previous results from Egypt by extending the working area to Jordan and including planktic foraminiferal assemblages and whole-rock stable isotope results.

Similarly, in Tunisia, a paleoenvironmental change is recorded during the same interval, although there it was not marked by a black shale bed and associated anomalous microbiota.
4 Geological setting and Lithology

The extensive epicontinental basins on the southern margin of the Mediterranean Tethys (Fig. 2) supply excellent opportunities for microbiotic studies along paleobathymetric gradients, allowing us to evaluate the relation between trophic regimes and their biota. In fact, numerous well-exposed outcrops, yielding well-preserved microfossils for paleoenvironmental research are easily accessible in several localities. This region was characterized by centres of upwelling and high productivity during certain periods within the Maastrichtian-Paleocene (Almogi-Labin et al., 1993; Speijer, 1994), confirmed also in modelling studies (i.e. Huber et al., 2003).

Samples from Jordan (outcrops at Gebel Qurtayssiat and Shaubak) and Tunisia (outcrops at Elles, Ain Settara) were collected during two fieldworks during the first year of the PhD project. Samples from the other localities in Egypt and Tunisia were collected earlier by various teams of researchers and made available for study.

Fig. 2 Tethys map during the Early Paleogene, modified after Widmark and Speijer (1997).
The grey circles indicate the studied localities: 1-Tunisia; 2- Egypt; 3- Jordan

The studied localities were located along bathymetric transects on the continental margin, from middle neritic (50-100m) to upper bathyal (200-600m) paleodepth.

Tectonically, the late Mesozoic and Paleogene of Egypt can be subdivided into two major provinces, the unaffected “stable shelf” in the south (also known as Nile Basin) and the active “unstable shelf” in the north (Syrian Arc), (Said, 1990). Deposition of hemipelagic sediments was controlled by this tectonic regime that has probably been active since the late Cenomanian (Al Rifaiy and Cherif, 1987; Bauer et al., 2003). The unstable shelf is characterized by small-scale facies variations within a basin-and-swell morphology,
exhibited in shallow water ramp carbonates in North Galala and Sinai, and deeper-water intrashelf marls toward South Galala (Scheibner, 2001).

Instead, all the localities studied in this work are situated on the stable shelf (Said, 1990; Youssef, 2003). The Jordanian localities belong to the stable shelf, but are situated in a basin that experienced tectonic instability because of its vicinity to the Syrian Arc (Abed and Amireh, 1999; Kuss et al., 2003). In the modern configuration, the Jordanian localities are shifted ~100 km N in response to sinistral movements along the Dead-Sea transform fault (Garfunkel and Ben-Avraham, 1996).

In Tunisia, by the end of the Cretaceous, the Jeffara and Kasserine Islands and other small areas emerged in southern and central Tunisia. Kasserine Island separated a basin in the north from a narrow basin in the south. The studied localities were part of the northern basin (Zaier et al., 1998), also known as the Tunisian Trough (Burollet, 1956; Salaj, 1980). Hemipelagic marl-shale sedimentation occurred in open marine conditions, but with significant terrigenous input from Kasserine Island. Paleocene sediments in the Tunisian Trough are up to 500 m thick due to a high subsidence rates and sediment input and thinner towards Kasserine Island (Zaier et al., 1998).

In the whole area, the Paleocene is mainly characterized by the deposition of shaley and chalky monotonous marls (Fig. 1) overlain by Eocene limestones. These marls belong to the El Haria Formation in Tunisia, to the Dahkla and Esna Formations in Egypt and to the Muwaqqar Chalk Formation in Jordan.

In the investigated successions, sea level changes can be discerned through variations in sedimentological and faunal composition and, rarely, in lithological changes. Speijer and Wagner (2002) described a sea-level fluctuation across the PETM in Egypt. Moreover, during the middle Paleocene the sequence boundary Sel1 (Hardenbol et al., 1998) is consistently recognized in the studied area, allowing a correlation between the Middle East and Tunisia and to the global record.

### 5 Proxies: concept and approaches

Reconstructing environmental conditions in the fossil record implies to use measurable variables as an indicator of biological, physical and chemical parameters, which cannot be directly measured. These measurable descriptors for unobservable variables are called “proxies” (Wefer et al., 1999).

In this research, we investigated foraminifera and organic dinocysts assemblages, and relate proxies, which have been successfully applied in a large number of recent studies and in the fossil records. Additionally, geochemical parameters such as carbonate content and stable isotopes are investigated. Whilst studies on the present-day environment have the opportunity to directly test their assumption and combine biotic evidences with measurable physical and chemical parameters, this is prevented in the fossil record. Moreover, often we are dealing with taxa, which are not extant in the modern ocean, but at best, they
morphologically resemble extant taxa. Additionally, weathering, diagenesis, and taphonomical processes lead to paleoenvironmental reconstructions full of uncertainties and suppositions. Since no proxy is truly sensitive to only one environmental parameter, for a most reliable reconstruction, a multi-proxy approach is preferable. This procedure should reduce the potential of misinterpretations. For instance, in Tunisia the application of proxies based on organic dinocysts and foraminifera successfully allowed to reconstruct a more reliable trend than on the basis of each group individually. For instance, the protoperidinioid/gonyaulacoid ratio has been developed in addition to the classical peridinioid/gonyaulacoid ratio, which seems to better approximate the productivity variation in this area. Unfortunately, unexpected encountered problems such as absence of palynomorphs in the Middle East do not allow applying this multi-proxy approach on a larger scale.

5.1 Planktic and benthic foraminifera

Foraminifera are protozoans which secrete a skeleton and they are mainly subdivided in benthic (living within or on top of the sea floor) and planktic (living in the water column) species. Their importance for environmental and paleoenvironmental studies is well known and an enormous amount of research is devoted to these organisms. They have been reported from a wide range of marine environments from coastal marshes to abyssal plains, hence their importance for (paleo)environmental reconstructions. Whilst their distribution is controlled by several factors (i.e. nutrients and oxygen availability, temperature), they can be applied as proxy for a number of different parameters. The potential fossil preservation is high, explaining their large use in the fossil record. In fact, the studied Paleocene marls yield generally rich and rather well preserved assemblages. For the purpose of this research, we mainly focused on planktic foraminifera to reconstruct water column conditions and estimate paleoproductivity variations. Additionally, planktic foraminifera are significant for biostratigraphic purposes, enabling correlation between the studied localities. The numbers of each genus in the planktic assemblages, the ratio on the total foraminiferal number (P/B ratio) and the numbers of planktic foraminifera per gram of sediments (PFN) have been quantified. The P/B ratios are integrated with marker benthic foraminifera in order to determine paleobathymetry. Major climatic and oceanographic changes during the Paleocene are expressed in changes in benthic and planktic foraminiferal assemblages (Chapters II-VI).
5.2 Organic dinoflagellate cysts

Dinoflagellates are unicellular eukaryotic organisms, mainly marine, characterized by a motile stage and (some of them) by a benthic stage, producing a cyst. Whereas the motile stage generally does not fossilize, for paleoenvironmental studies the cysts preserved in sediments provide the most important information. Many dinoflagellates are planktic organisms in marine and freshwater environments, a few are symbionts or parasites. They are characterized by having a variety of nutritional strategies; most are autotrophic, others are heterotrophic, and some act as photosymbionts. The high-resistant cysts have a great preservation potential. This group has been successfully adopted in a number of researches for reconstructing for instance sea-surface productivity, sea-level change, temperature, salinity, stratification and circulation of water masses.

Changes in productivity are considered to influence the ratio between the heterotrophic protoperidinioid and the autotrophic gonyaulacoid dinocysts (Almogi-Labin et al., 1993); therefore, the peridinioid/gonyaulacoid ratio is a good approximation of a paleoproductivity signal in the fossil record.

However, their preservation is extremely sensitive to oxygen availability. In the working area, dinocysts assemblages are preserved only in Tunisian material (Chapters II-III). In samples from Egypt and Jordan they appear oxidized through weathering.

5.3 Stable isotopes of oxygen and carbonate

The importance of carbonate stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) in paleoceanography was recognized already in 1955, when Emiliani first published a work on the relation between Pleistocene temperature and oxygen isotopic composition in planktic foraminiferal shells. $\delta^{13}C$ and $\delta^{18}O$ of fossil planktic foraminifera are good proxies for estimating (paleo)productivity, and (paleo)temperature and (paleo)salinity, respectively. Since foraminifera from Paleocene marls are often filled with secondary calcite from diagenetic processes, the signal is usually contaminated. Being aware of this problem, in this work stable isotope are performed only on whole-rock samples. The signal should still have preserved some of the main trends, despite diagenetic overprinting (Chapters III –VI).

5.4 Carbonate Content

The carbonate content is predominantly constituted by biogenic components, thus may add information on paleoproductivity variation. In the ocean and above the continental slopes, the carbonate production is dominated by phytoplankton and zooplankton, whereas in near shore environments, benthic organisms are the major sources (Rühlemann et al., 1999). Mainly, in shallow water settings, the terrestrial input plays an important role; in particular, low values can indicate increased terrigenous proportions. However, in arid areas, deep weathering of exposed rocks is of importance and low carbonate values might result from this (El Kammar and El Kammar, 1996). By combining carbonate content with numbers of
planktic foraminiferal and the planktic/benthic ratio, carbonate dissolution can be estimated (i.e. Chapter V).

These topics are summarized in six chapters, which are in the process to be published as separate papers.

In Chapter II, an integrated paleoecological analysis of quantitative distribution patterns of Paleocene (Planktic foraminiferal Zones P1b-P4) organic dinocysts and benthic foraminifera from the El Kef section (NW Tunisia) is proposed. We focus on combining the signal from surface-water and sea-floor proxies in order to refine paleoproductivity and paleobathymetry reconstruction of the area. Moreover, we establish a succession of biofacies, characterized by different paleoenvironment conditions. Our records indicate that the environment evolved from an initial oligotrophic, open marine, outer neritic to upper bathyal setting in the lower Paleocene, towards a more eutrophic inner neritic setting, influenced by coastal upwelling by the end of the Paleocene. From the base of planktic foraminifera Zone P4 onwards, an increase of inner neritic dinocysts of the Areoligera group, disappearance of deeper-water benthic foraminifera and increasing dominance of shallow-marine taxa (several buliminids, Haplogragmoides spp., Trochammina spp.) are indicative of shallowing of ~150 m (from ~200 to ~50 m). Superimposed on the overall trend, third order sea-level fluctuations have been identified. Paleoproductivity indicators (notably protoperidinioid dinocysts and buliminids) show a trend from an oligotrophic to a eutrophic setting.

This work has been carried out in cooperation with Tanja J. Kouwenhoven and Henk Brinkhuis (both Utrecht University) and Robert P. Speijer (K.U.Leuven).

In Chapter III, the NW Tunisia area has again been the focus, and the Danian-Selandian transition has been studied in detail. Three localities at shallow-outer neritic (Ain Settara) and deeper-outer neritic (El Kef and Elles) are investigated. An integrated biostratigraphic study based on planktic foraminifera and calcareous nannofossils enable a more detailed correlation of the localities. Evaluation of the P/B ratios and benthic foraminifera provides additional information on the bathymetry. Furthermore, distance from the coast is discriminated by the organic dinocysts. Geochemical proxies, such as carbonate and oxygen stable isotopes and carbonate content also enhanced the interpretation. By combining several proxies, a major change in the paleoenvironmental setting is described across the Danian-Selandian transition. From an oligotrophic open marine setting in planktic foraminifera Zones P2-P3a, a shallower phase toward rich-nutrient environment is evidenced starting at the base of Subzone P3b.

This part was in cooperation with Robert P. Speijer (K.U.Leuven), Henk Brinkhuis (Utrecht University), Jan Smit (Free University of Amsterdam), Etienne Steurbaut (RBINS Brussels and K.U.Leuven).
In **Chapter IV**, the Middle East is the focus of our research. As a continuation of the study on the middle Paleocene and with the aim to compare these areas, we focus on the Danian-Selandian transition in Egypt and Jordan. A similar transect from middle neritic (70-150m: Gebel Duwi) to outer neritic (150-250m: Gebel Aweina, Gebel Qreiya, Gebel Nezzi, Gebel Qurtayssiat) to upper bathyal (250-300m: Shaubak) is studied. A partially laminated dark-bed rich in fish remains is associated to anomalous planktic and benthi c foraminifera and calcareous nannofossils assemblages during a brief interval, named as “Neoduw i event”. In particular a bloom of the shallow-water taxon *Neoeponides duwi* on the sea floor, associated with a peak of planktic foraminifera *Acarinina* in the Nile Valley and small-sized *Morozovella* in Gebel Duwi and Jordan indicate changes in the paleoceanographic conditions in relation to climatic change. In fact, in The Nile Valley, enhanced freshwater supply due to increased runoff and precipitation is speculated. Conversely, at the same time, an upwelling system is set up in the eastern part of the basin. Sedimentological and biotic variations suggest similar depositional processes as for the PETM in the same area, suggesting the “Neo-Duwi event” as a possible hyperthermal event.

This part was carried out in cooperation with Robert P. Speijer (K.U.Leuven), Eliana Fornaciari (University of Padua), Birger Schmitz (University of Lund), Dick Kroon (Free University of Amsterdam), Ahmed Garaibeh (NRA, Amman).

In **Chapter V**, the uppermost Paleocene is investigated across a middle neritic to upper bathyal transect in the Middle East, in the same area as previously studied in chapter IV. In particular, the planktic foraminiferal turnover and the diversification of new taxa across the Paleocene-Eocene thermal maximum (PETM) are evaluated. Dissolution affects the planktic assemblages, especially in the marls below the PETM as evidenced by high numbers of *Subbotina*, fluctuating P/B ratios and low numbers of planktic foraminifera per gram. This pattern aspect is probably a consequence of deep weathering. Despite this taphonomic overprint, we observe that well diversified planktic foraminiferal assemblages of Subzone P5a abruptly change into oligotaxic assemblages dominated by *Acarinina* during the PETM. Because various biotic and geochemical proxies indicate increased nutrient supply to the basin, we argue that the blooming of *Acarinina* is not indicative of oligotrophic conditions. Instead, we speculate that (low-trochospiral) *Acarinina* may have been better adapted to thrive under stressed environmental conditions, because they possibly hosted symbionts different from those in *Morozovella*. Finally, it is inappropiate to subdivide Zone P5 on the basis of the occurrence of *Acarinina sibaiyaensis*, because this taxon occurs in Egypt and off Senegal well before the PETM. Instead, *A. multicamerata* sp. nov. is proposed as biozonal marker of Subzone P5b.

This work has been carried out in cooperation with Robert P. Speijer (K.U.Leuven).
In Chapter VI, the impact of the PETM on planktic and benthic foraminiferal assemblages at Dababiya (Egypt) has been evaluated. Because this locality has been chosen to define the GSSP of the Paleocene/Eocene boundary (Ouda and Aubry, 2003), it is important to provide a detailed overview of the biotic assemblages in this outcrop.

During the late Paleocene, planktic and benthic foraminiferal communities reflected high diversity and high densities, suggesting mesotrophic conditions with relatively high productivity and (fluctuating) low oxygen levels. At the P/E boundary diversity and densities dropped steeply, coinciding with the global extinction level of benthic foraminifera (Benthic foraminifera extinction event: BEE) and start of the Carbon Isotope Event (CIE), which marked the onset of the PETM. During the first stages of the PETM, non-calcareous laminated clay was deposited under anoxic conditions and only one sample contained mainly poorly preserved planktic foraminifera (*Acarinina*). During the middle PETM low-diverse/high-dominance benthic fauna appeared, indicating occasional re-oxygenation of the basin followed by short periods of repopulation of the benthic environment (e.g., *Anomalinooides aegyptiacus*, *Stainforthia* spp.). The planktic community started to diversify, although shallow-dwelling taxa remained dominant (*Acarinina*, *Morozovella*) indicating poor conditions for deep-dwelling taxa. During the late PETM, the diversity and densities of the benthic and planktic faunas first increased strongly, but during the final stages of the late PETM densities and diversity slightly decreased. Planktic faunas remained diverse with both deep and shallow-dwelling taxa. *Bulimina callahani* dominated the benthic assemblage, which is thought to be representative of low oxygen levels and/or high productivity.

This work has been carried out in cooperation with Sander Ernst and Robert P. Speijer (both K.U.Leuven).

In Chapter VII, a synthesis of this work is proposed. Correlation across the Danian-Selandian transition between the Middle East and Tunisia is investigated. Additionally, a comparison with Zumaya (northern Spain) is provided, since this locality has been proposed to host the GSSP for the definition of the Danian/Selandian boundary (Schmitz et al., 1998). Furthermore, a comparison between the Danian-Selandian transition and the Paleocene-Eocene thermal maximum is also evaluated trying to underline similarities and differences.
References


CHAPTER II

Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, NW Tunisia)

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CHAPTER II

Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, Tunisia)

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Abstract

Integrated analysis of quantitative distribution patterns of organic walled dinoflagellate cysts (dinocysts) and benthic foraminifera from the Paleocene El Kef section (NW Tunisia) allows the reconstruction of sea-level and productivity fluctuations. Our records indicate that the environment evolved from an initially oligotrophic, open marine, outer neritic to upper bathyal setting towards a more eutrophic inner neritic setting, influenced by coastal upwelling by the end of the Paleocene. An overall second order change in paleodepth is reflected by both microfossil groups. From the base of planktic foraminifera Zone P4 onwards, the main phase of shallowing is evidenced by an increase of inner neritic dinocysts of the Areoligera group, disappearance of deeper-water benthic foraminifera and increasing dominance of shallow-marine taxa (several buliminids, Haplophragmoides spp., Trochammina spp.). The total magnitude of this shallowing is obscured by interaction with a signal of eutrophication, but estimated to be around 150 m (from ~200 to ~50 m). Superimposed on the overall trend, third order sea-level fluctuations have been identified and correlated to sequences in other regions. Paleoproductivity indicators (notably protoperidinoid dinocysts and buliminids) show a trend from an oligotrophic to a eutrophic setting.
1 Introduction

The Paleogene has become appreciated as a climatically highly dynamic period, involving the transition from the near ice-free world of the Cretaceous to the glacially dominated world of the Neogene (Zachos et al., 2001). In this context, the global warming trend recorded during the Paleocene and culminating in the early Eocene represents an important phase of biotic and environmental change (Zachos et al., 2001; Wing et al., 2003; Zachos et al., 2003; Billups et al., 2004). Yet, relative to studies focusing on the Paleocene/Eocene thermal maximum (PETM) comparatively little is known of the preceding, longer-term paleoceanographic changes and climate dynamics. In addition, while ocean drilling is providing new insights in Paleocene oceanography, ancient continental margins remain poorly studied.

Here, we report on the succession at El Kef, NW Tunisia, a site located at the southern margin of the Tethys. Compressive tectonics resulting from convergence of the African and Eurasian plates prevailed in this area during the Cenozoic (Zaier et al., 1998). Shallow seas fringing the Tethys covered Tunisia in the late Mesozoic and early Cenozoic, and by the end of the Cretaceous the Jeffara and Kasserine Islands and other small areas emerged in southern and central Tunisia (Fig. 1). Kasserine Island separated a basin in the north from a narrow basin in the south. The El Kef area (Fig. 1) was part of the northern basin (Zaier et al., 1998), also known as the Tunisian Trough (Burollet, 1956; Salaj, 1980; Bobier et al., 1991; Burollet, 1991). Hemipelagic marl-shale sedimentation occurred in open marine conditions, but with significant terrigenous input from Kasserine Island, and intermittent influx from emerged land located to the west of El Kef (Adatte et al., 2002). Paleocene sediments in the Tunisian Trough are up to 500 m thick due to a high subsidence rate and sediment input. Paleocene sediment thickness reduces towards Kasserine Island (Zaier et al., 1998).

The El Kef section (Figs. 1, 2) exposes the El Haria Formation, spanning the upper Maastrichtian to Eocene and consists mainly of brown-grey homogeneous marls and shales. It overlies the chalky limestones of the Campanian to lower Maastrichtian Abiod Formation, and is overlain by limestones of the Ypresian Metlaoui Formation. Throughout the upper Maastrichtian and Paleocene the sediments were deposited in a shelf to upper-slope setting (Brinkhuis and Zachariasse, 1988; Keller et al., 1995; Speijer and Van der Zwaan, 1996; Kouwenhoven et al., 1997; Galeotti and Coccioni, 2002). The section was chosen in view of its expanded and well-exposed nature, although four intervals (8 to 15 m thick) could not be sampled. A sample set covering the Paleocene, and including the Cretaceous-Paleogene (K/P) boundary (~65 Ma) was collected in 1982 by A. J. T. Romein and J. Smit near the village of El Kef (Fig. 1). The biostratigraphy is fairly well established (Salaj, 1980; Brinkhuis et al., 1994; Kouwenhoven et al., 1997).
Most previous studies concentrated on the Cretaceous/Paleogene boundary of the El Kef section, and dinocysts, benthic and planktic foraminifera from the lowermost seven meters of the Paleocene, comprising the recovery after the K/P boundary were studied in great detail (Smit and Romein, 1985; Brinkhuis and Zachariasse, 1988; Keller, 1988a; Keller, 1988b; Keller et al., 1995; Speijer and Van der Zwaan, 1996; Brinkhuis et al., 1998; Culver, 2003). Studies of the entire Paleocene interval were performed on ostracodes (Donze et al., 1982; Peypouquet et al., 1986), calcareous nannoplankton (Perch-Nielsen, 1981), and planktic and benthic foraminifera (Salaj, 1980; Kouwenhoven et al., 1997). A preliminary report on the qualitative dinocyst distribution was published in Brinkhuis et al. (1994).

Whereas most previous studies were based on one microfossil group, this paper presents new quantitative palynological data, integrated with existing benthic foraminiferal data. We focus on the Danian to lower Thanetian interval (~64.8-56.7 Ma), corresponding to planktic foraminifera Zones P1b to P4 (Berggren et al., 1995) and calcareous nannoplankton Zones NP1 to NP7/8 of Martini (1971). By integrating sea-surface (dinocysts) with sea-floor (benthic foraminifera) groups, our study aims to reconstruct paleoenvironmental changes with emphasis on sea level and paleoproductivity. The main trends recorded in both groups can be considered more reliable than signals from each group individually. Hence, this procedure should reduce the potential of paleoenvironmental misinterpretations.
2 Methods

2.1 Palynological data

Thirty-six samples (AFN 594 to AFN 631) were studied, covering 190 m of the section. The samples were processed according to standard palynological techniques (Brinkhuis et al., 2003). The residues were sieved using a 10µm mesh-sieve and prepared on slides using glycerin jelly. The slides are stored at the Laboratory of Paleobotany and Palynology, Utrecht University, The Netherlands.

Palynomorphs were subdivided in eight categories (i.e. bisaccate pollen, other pollen and spores, acritarchs, determinable dinocysts, Leiosphaeridia spp., Pterospermella spp., indeterminable dinocysts, and inner walls of foraminifera (if more than 3 chambers were encountered). Non-saccate pollen and spores were identified and grouped together as terrestrial palynomorphs.

Dinocysts were counted up to 100 determinable cysts where possible. Dinocyst taxonomy is in accordance with Williams et al. (1998). In order to obtain the main variations of the paleoecological signal along the succession, the taxa have been grouped based on their broad paleoecological characteristics (Appendix I).

Several ratios that are often used as paleoenvironmental proxies were calculated. Eukaryotic sea-surface productivity (SSP) has been estimated using the ‘classical’ P/G ratio (peridinioid/gonyaulacoid), which includes all peridinioid cysts (P cysts) and is calculated as $P/G = nP/(nP+nG)$. In addition, we generated the protoperidinioid/gonyaulacoid ratio (Pp/G), which only includes cysts of extant heterotrophic motile protoperidinioids (Pp) and is calculated as $Pp/G = nPp/(nPp+nG)$.

The ratio between inner neritic and outer neritic dinocysts (IN/ON) has been calculated applying the formula $IN/ON = nIN/(nIN+ON)$ (e.g., Versteegh, 1994).

To estimate the relative contributions of terrestrial versus marine organic material, the S/D ratio was calculated, applying the formula $S/D = nS/(nD+nS)$, with $S$=number of sporomorphs (terrestrial) and $D$=number of dinocysts and marine acritarchs (Versteegh, 1994).

2.2 Statistical analyses

The census counts of benthic foraminifera were re-evaluated for the present study. In order to group the benthic taxa, the relative frequency matrix was condensed by eliminating ill-defined groups, and taxa occurring in frequencies below 6%. The resulting matrix (Appendix III) was introduced in R-mode hierarchical clustering (SPSS standard software, Pearson correlation).

With the purpose to establish biofacial units, we performed a Q-mode cluster analysis on the combined data sets (i.e., the relative frequencies of dinocyst and benthic foraminiferal taxa), in order to cluster the samples characterized by similar biofacies (SPSS standard software, Pearson correlation).
3 Results

3.1 Dinocyst assemblages

Nearly all samples contain palynological assemblages dominated by marine palynomorphs. Selected groups (cf. Appendix I) are plotted in Figure 2.

Fig. 2 Lithology, biostratigraphy (calcareous nanoplankton and planktic foraminifera), major organic dinocysts events and sample positions in the El Kef section are plotted against the relative frequency of organic dinocysts. Personal observations on planktic foraminifera allow identification of *Globanomalina pseudomenardii* in sample AFN 618, and thus the base of planktic foraminifera Zone P4 has been repositioned to a stratigraphically lower level.

The dinocysts taxa are grouped together as proposed in Appendix II. Within the *Fibrocysta* group, the relative abundance of *Kenleyia* spp. is plotted in a darker grey color. *Apectodinium* spp. is plotted with a different percentage scale than the other taxa.

The *Fibrocysta* group, consisting of typical neritic cysts, is one of the main components of the assemblage. The peak occurrence in the lower Paleocene is due to the high abundance of the *Kenleyia* complex. High percentages of the *Fibrocysta* group (>40%) in planktic foraminifera Zones P3b and P4 are due to *Fibrocysta* spp. The *Cerodinium* group includes cavate peridinioid cysts. Maximum abundance is reached in Zones P1b and P3 (~ 40%). In the upper part of the studied interval (at 163 and 178 m) the abundance of the *Cerodinium*
group increases again. The *Areoligera* group, which includes extinct taxa that were dominant in inner neritic and coastal environments, becomes more common from the base of planktic foraminifera Zone P4 and reaches a maximum abundance of 30% in the upper part of the studied interval. The *Lejeunecysta* group (protoperidinioid cysts) shows maximum abundances from the base of Zone P4 onwards and dominates the assemblage (>80%) in sample AFN 624 within Zone P4. This group is commonly associated with inner neritic environments characterized by high eukaryotic productivity. *Spiniferites*, which is considered a cosmopolitan taxon often associated with open marine conditions, occurs throughout the section. The typical offshore taxon *Impagidinium* only occurs in the background.

Despite their low relative abundance, *Apectodinium* spp. are plotted because of their worldwide importance during the Paleocene-Eocene transition. The lowest occurrence of these representatives of the wetzeellioid lineage was found in sample AFN 615 at the base of planktic foraminifera Subzone P3b (Brinkhuis et al., 1994). Above this level it reappears as single occurrences.

### 3.2 Benthic assemblages

R-mode clustering of the benthic foraminiferal assemblages resulted in two main clusters (Fig. 3). Cluster I groups species that generally decrease upwards in numbers (e.g. *Osangularia plummerae; Pulsiphonina prima*). Within this cluster sub-cluster IA (including *Gavelinella beccariiformis*) is present in the lower part of the section and disappears altogether above 110 m. The assemblage in cluster IB dominates the benthic record from planktic foraminifera Zones P1c to basis P4 and strongly decreases in the course of Zone P4.

Cluster II groups species that are more common in the upper part of the section (e.g. buliminids, *Haplophragmoides* spp.). Sub-cluster IIA groups the buliminids, increasingly abundant from upper Subzone P3b upwards and dominant in upper Zone P4. Sub-cluster IIB groups mainly *Lenticulina* spp. and the arenaceous taxa *Haplophragmoides* and *Trochammina* spp., which dominate the benthic record in the lower Zone P4.

Benthic diversity is relatively constant at moderately high levels until the lower part of Zone P4, where it decreases and it is significantly reduced at the basis of nannoplankton Zone NP7. Between 60 and 125 m, a decrease of the %P suggests a decrease of water depth. However, the percentage planktics (%P) is less reliable as a paleodepth estimate in parts of planktic foraminiferal Zones P4 (NP7), due to poor preservation of foraminiferal faunas.
3.3 Proxies and Q-mode clustering: biofacial succession

The dinocyst and benthic assemblage data, biotic proxies and Q-mode clustering were used to define biofacial units (Fig. 4, 5). These units serve as a tool to describe the paleoenvironmental history of the succession. Four main biofacies units can be recognized each subdivided into two sub-facies.

**Biofacies 1** is characterized by well-diversified assemblages. Although inner neritic taxa are slightly dominant in the dinocyst assemblage, the benthic assemblage is dominated by outer neritic taxa (cluster IA; 24% *Pulsiphonina prima*). Sub-facies 1a is present in the lower P1b Subzone (corresponding to NP1 and lowermost NP2) and shows relatively high P/G and Pp/G ratios. Sub-facies 1b is not confined to a certain period; it is present in a few Danian samples and in Subzone P3b (in sample AFN 615 at 98m).

**Biofacies 2** occurs in Subzone P1b, the interval that includes the limestone beds. The biofacies of some samples slightly deviate from the general biofacies in this interval. The *Fibrocysta* and *Spiniferites* dinocyst groups, and deeper-water benthic foraminifera of cluster IA are common. The P/G and Pp/G ratios are low and decrease upwards. Sub-facies 2a is also characterized by a maximum abundance of *G. beccariiformis* (30%), by two maxima in terrestrial palynomorphs and by a maximum abundance of outer neritic dinocysts (low IN/ON ratio). Sub-facies 2b corresponds to the interval with the limestone beds, recording a peak occurrence of *Kenleyia* spp. (80%). Furthermore, the IN/ON ratio increases and the abundance of *G. beccariiformis* strongly decreases.
**Biofacies 3** is dominated by the *Fibroycysta* and *Cerodinium* dinocyst groups and by outer neritic benthic foraminifera of cluster IB. The assemblages are well diversified and the difference between the P/G and Pp/G ratios is at a maximum. At 73 m, an elevated S/D ratio corresponds with a maximum abundance of peridiniod cysts (*Paleocystodinium* spp.), a relatively high IN/ON ratio and a decrease of the %P. In Subzone P3b (sample AFN 615, 98m) sub-facies 1b is found to separate sub-facies 3a and 3b. In this sample the first occurrence of *Apectodinium* is observed, in association with a peak of the *Cerodinium* group. Sub-facies 3a is also present in Zone NP2 at 33 m, and in the upper Zone NP7. Sub-facies 3b occurs briefly in lower Zone NP2, but is mainly found in Zones P3b and lower P4, where the main paleoenvironmental change becomes apparent. This change is characterized by a decrease in %P and a transition of the benthic assemblage.

**Fig. 4.** Dinocysts distributions, benthic foraminiferal assemblages, planktic/benthic ratio, IN/ON ratio, Pp/G and P/G and S/D are represented. The dashed line indicates the actual values of the IN/ON, while the grey curve represents the 3 point moving average.

The biofacies proposed in this work are here represented next to the ecozones of Donze et al. (1982) and Peypouquet et al. (1986).
Frondicularia phosphatica, a relatively large benthic foraminiferal species not encountered in the 125-595 µm fraction of benthic foraminifera, is extremely abundant in a foraminiferal packstone, channel-like deposit in the lower Zone P4 (at the base of NP6).

Biofacies 4 records major changes in the assemblages and derived proxies. The IN/ON ratio is relatively high: inner neritic dinocysts dominate this interval. The P/G and Pp/G ratios show a strong similarity and abruptly increase to reach a maximum. The benthic diversity and the P/B ratio decrease and outer neritic benthic foraminifera virtually disappear. Sub-facies 4a is characterized by the high productivity Lejeunecysta group and by considerable changes in the benthic assemblages. In the silty interval between 160 and 180 m sub-facies 4b predominates, mainly characterized by shallow and high productivity dinocysts (Lejeunecysta and Cerodinium groups) and benthic foraminifera (buliminids). Frondicularia phosphatica occurs regularly in the course fractions (>595 µm) of the washed residues. Sub-facies 3a temporarily reappears at 170 m. Sub-facies 4a is recorded again in the uppermost part of the studied section.

**Fig. 5.** Q-mode dendrogram of the complete dataset of organic dinocysts and benthic foraminifera. Clusters represent biofacies units.
4 Discussion

4.1 Paleoenvironment, biofacies and ostracode ecozones

The K/P boundary interval and the following recovery of ecosystems are of such complex character that we refrained from incorporating them in our study. This much debated time slice was studied in great detail based on high-resolution records of, among others, dinocysts and benthic foraminifera (e.g., Brinkhuis and Zachariasse, 1988; Keller, 1988a; Speijer and Van der Zwaan, 1996; Brinkhuis et al., 1998).

In our post-recovery record we recognize two main intervals. The environment evolved from an open marine, oligotrophic setting in the lower Paleocene towards an inner neritic and more eutrophic setting in the upper Paleocene. Despite the monotonous marls and the scarcity of lithological changes, the palynological and foraminiferal assemblages and proxies indicate major paleoenvironmental changes that are reflected by the biofacies.

**Biofacies 1** indicates a low to moderately productive outer neritic, open marine environment with diverse assemblages. Offshore oligotrophic dinocyst taxa (*Impagidinium* spp.) occur and the abundance of typical inner neritic taxa (*Lejeunecysta* group, *Areoligera* group) is low. The benthic taxa were described from relatively oligotrophic environments at outer neritic to upper bathyal paleodepths in Egypt (e.g. *Gavelinella beccariiformis*, *Pulsiphonina prima*: Speijer and Schmitz, 1998). Whereas sub-facies 1a characterizes the lowermost part of the section, sub-facies 1b indicates that similar open marine conditions recurred at several short-lived periods during the Danian.

**Biofacies 2** is comparable to biofacies 1. Differences appear to be mainly related to movements in relative sea level. In sub-facies 2a, a short-lived maximum occurrence of *G. beccariiformis* (>30%) together with a low IN/ON ratio may indicate a period of deepening. Sub-facies 2b may reflect a subsequent shallowing. The S/D ratios indicate low sediment supply from land, which is in line with limestone deposition. The *Fibrocysta* group dominates the middle Subzone P1b with a peak occurrence of *Kenleyia* spp. This group joins a number of autotrophic cysts, characterizing a variety of inner neritic environments. The *Kenleyia* complex is thought to have had a preference for shallow to brackish water and tropical conditions, as indicated by its high abundances concomitant with the bloom of *Apectodinium* during the PETM (Crouch et al., 2003). Its dominance may also be related to enhanced stratification of surface waters (compare Reichart et al., 2004), but this explanation is not supported by evidence in the other assemblage and proxy data. The occurrence of the *Kenleyia* peak might indicate a shallowing phase, as corroborated by the decreasing abundance of *G. beccariiformis*.

In **biofacies 3** the P/G and Pp/G ratios show maximum divergence. As none of the other proxies indicates elevated productivity levels, we tend to rely on the Pp/G ratio that reflects relatively low productivity in a fairly stable paleoenvironment. Sub-facies 3a is dominated by dinocysts of the *Cerodinium* group and the FO of *Apectodinium* is recorded in the top of this
sub-facies. The subsequent dominance of *Fibrocysta* spp., together with increasing IN/ON ratios and decreasing P/B ratios indicates shallowing during deposition of sub-facies 3b, and marks the onset of environmental instability.

**Biofacies 4** differs strongly from earlier biofacies types and reflects an important change in the paleoenvironment. A drastic increase of inner neritic dinocysts of the *Areoligera* and *Lejeunecysta* groups concurs with a turnover in the benthic assemblages. The increase of *Areoligera* spp. precedes the main increase of *Lejeunecysta* spp., suggesting that shallowing preceded an increase of productivity. Benthic foraminifera indicate a similar change in paleoenvironmental conditions. Benthic sub-cluster IIB groups the arenaceous taxa *Trochammina* and *Haplophragmoides*, described from inner neritic and coastal (*Haplophragmoides* spp.) environments, respectively (LeRoy, 1953; Luger, 1985; Saint-Marc and Berggren, 1988; Speijer and Schmitz, 1998). These taxa show peak occurrences between 140 and 160m. Calcareous benthic foraminifera appear to be suppressed in this interval, which may be an artefact related to dissolution of calcareous tests. Subsequently the dominance of sub-cluster IIA, including common buliminids, indicates increasing productivity.

The occurrence of *Frondicularia phosphatica* and common fish remains in this interval suggests limited sea-floor oxygenation. However, the absence of laminations and the presence of epibenthic taxa (*Cibicides/Cibicidoides* and *Anomalinoides* spp.) support a scenario of increased productivity and lowered oxygen levels rather than a prolonged and severe oxygen deficiency at the sea floor. The upper Paleocene benthic foraminiferal assemblage of El Kef is typical of highly productive inner to middle neritic environments in the southern Tethyan region, possibly as a result of trade wind induced upwelling (e.g., Speijer et al., 1996). Modelling studies confirm that the North African margin was probably affected by north-eastern winds during the early Paleogene. These were driven by strong tropical-subtropical temperature gradients and are held responsible for a southeast to west coastal current (Huber and Sloan, 2000) with significant upwelling along the North coast of Africa as a consequence (Huber and Sloan, 2000; Huber et al., 2003).

In general there is a fairly good agreement between our data and ostracode records (Donze et al., 1982; Peypouquet et al., 1986) in the overall paleoenvironmental evolution and position of the main biotic transitions at El Kef. However, in more detail our data do reveal some discrepancies with the interpretation based on the ostracodes (Donze et al., 1982; Peypouquet et al., 1986; Fig. 4, 6). The paleodepth estimate based on the ostracode record is generally somewhat deeper than our estimate based on the combined dinocyst and benthic foraminiferal records. Other discrepancies concern sea-floor oxygenation.

Ostracode ecozone 5 correlates with biofacies 1 and 2 of this study and is thought to be characterized by upwelling in an upper epibathyal, relatively well-oxygenated environment. Upwelling is, however, not evident in our data until much later in the Paleocene.
Ostracode ecozones 5’ and 6 and sub-facies 3a agree on an open marine, oligotrophic environment. However, the benthic foraminiferal assemblages do not support the slight decrease of oxygen at the sea floor suggested by Peypouquet et al. (1986).

Ostracode ecozone 7 mainly corresponds to sub-facies 3b. The ostracode assemblage records a shallowing trend from an upper bathyal to an outer neritic shelf environment starting at the transition from Subzones P3a to P3b (Peypouquet et al., 1986). During the same interval a decrease of the bottom water oxygen is recognized (Donze et al., 1982). In our view, sub-facies 3b indeed indicates shallowing, but rather from outer to inner neritic depths. We do not find good evidence for decreasing oxygenation at the sea floor.

Ostracode ecozone 8, corresponding to biofacies 4, is characterized by a poorly diversified ostracode fauna, indicating increasing productivity and decreasing bottom water oxygenation, which is in agreement with our data. During middle Zone P4, a temporary return to previous, slightly deeper and more oligotrophic conditions is inferred at the re-occurrence of biofacies 3. Lower values of the P/G and Pp/G ratios coincide with a peak of Areoligera spp. and a lower abundance of the buliminids, which points to a weakening of the upwelling system. This brief return of more open marine conditions is not recorded in the ostracode assemblages and was possibly not sampled in the earlier studies.

4.2 Evaluation of palynological proxies

In modern oceans, productive regions such as coastal and upwelling areas are characterized by a high relative amount of protoperidinioid dinoflagellate cysts (Versteegh, 1994; Batten, 1996; Firth and Clark, 1998; Prauss, 2001). Changes in productivity are considered to influence the ratio between the heterotrophic protoperidinioid and the autotrophic gonyaulacoid dinocysts. Thus the protoperidinioid/gonyaulacoid ratio (Pp/G ratio) can be used to estimate eukaryotic productivity, with high values representing eutrophic conditions (Reichart and Brinkhuis, 2003; Sluijs et al., 2005). Although not all modern Protoperidinium species seem to be heterotrophic (Dale and Fjellså, 1994), a number of studies have described the high abundance of these cysts in high nutrient inner neritic environments and in upwelling regions (Powell et al., 1996; Spranger et al., 2004). Most fossil peridinioid cysts (P cysts) such as Paleocystodinium, Cerodinium, Senegalam, and Spinidinium are morphologically comparable to modern protoperidinioids; however, their autecological affinity (heterotrophic or autotrophic) is unknown. Nevertheless, empirical information supports the idea that most fossil peridinioids were heterotrophic, and consequently the P/G ratio is the best approximation of a paleoproductivity signal (see discussion in Sluijs et al., 2005). The P/G ratio has been applied in a number of fossil settings (Powell et al., 1996; Brinkhuis et al., 1998; Zonneveld et al., 2001; Reichart and Brinkhuis, 2003; Roncaglia, 2004; Spranger et al., 2004). Next to a P/G ratio, we generated a Pp/G ratio for this study, which only includes cysts of extant heterotrophic motile protoperidinioids (Pp), such as Lejeunecysta spp. (Brinkhuis et al., 1998; Pross and Schmiedl, 2002; Sangiorgi et al., 2002;
Roncaglia, 2004). Eukaryotic sea-surface productivity (SSP) has thus been estimated using the ‘classic’ P/G ratio in addition to the Pp/G ratio.

From the middle Danian until the middle Selandian (upper Zone P3b), important differences distinguish the P/G and Pp/G ratios due to the scarcity of the extant *Lejeunecysta* group. Considering the P/G ratio, one would estimate two intervals of increased productivity. Instead, the Pp/G ratio indicates a relatively oligotrophic setting until the uppermost Zone NP6, which is in agreement with the other proxies.

From Zone NP7 to the top of the studied interval, the P/G and Pp/G ratios show a strong similarity due to the dominance of the *Lejeunecysta* group. Although it cannot be excluded that preferential preservation plays a role in the abundance of the peridinioid cysts (cf. Reichart and Brinkhuis, 2003), we consider this abrupt increase of protoperidinioid cysts to indicate an increase in paleoproductivity. Increasing productivity is also reflected by the benthic taxa: buliminids, *Anomalinoioides cf. aegyptiacus* and *F. phosphatica* (Speijer et al., 1996; Kouwenhoven et al., 1997). Taking the ecology of modern dinoflagellates into account, we consider the Pp/G ratio more reliable than the P/G ratio in terms of paleoproductivity.

The entire record is strongly dominated by the inner neritic dinocyst assemblage: the IN/ON ratio rarely falls below 0.5. This ratio represents the proportion of taxa typical of an inner neritic environment (*Fibrocysta*, *Areoligera* and *Lejeunecysta* groups) (Brinkhuis and Zachariasse, 1988; Brinkhuis, 1994; Powell et al., 1996; Sluijs et al., 2005; Pross and Brinkhuis, 2005) as compared to the neritic to oceanic taxa (e.g., the *Spiniferites* and *Impagidinium* spp.) (Brinkhuis and Zachariasse, 1988; Zonneveld et al., 1997; Devillers and de Vernal, 2000; Sluijs et al., 2005). Consequently, the generally upward increasing IN/ON ratio can be interpreted as an overall shallowing trend, interrupted by several temporary deepening phases. This is in agreement with depth estimates based on the benthic foraminiferal record, although some differences in paleodepth reconstructions occur in the lower Paleocene.

A large number of studies reveals the significance of the quantitative distribution of terrestrial palynomorphs in marine settings for sea-level reconstructions (e.g. Versteegh, 1994; McCarthy and Mudie, 1998; Santarelli et al., 1998; Prauss, 2001). According to McCarthy and Mudie (1998), the concentration of pollen and spores in marine sediments decreases exponentially with distance to shore. The S/D ratio, expressing the relative contribution of continentally derived organic material, is generally low, although single sample peaks occur in the lower part of the record. Only in a few cases the S/D peaks recorded in the Danian and lower Selandian correlate to increased P/G, Pp/G and IN/ON ratios, indicating a low correspondence between these proxies. In a regressive scenario one would expect a general increase of terrestrial palynomorphs. The generally low S/D values recorded in the section might be related to the distance of the sedimentation area from the source of terrestrial input. Alternatively, since we only consider relative values, an increase in terrestrial palynomorphs may be overshadowed by the high abundance of dinocysts under the high-productivity regime of the late Paleocene.
Fig. 6. Reconstruction of schematic sea-surface paleoproductivity and paleodepth. Sequence boundaries of Hardenbol et al. (1998) recognized in this record are indicated to the right.

### 4.3 Paleobathymetry: comparison with regional and global sea-level records

An overall second order change in paleodepth is recognized in the Paleocene of El Kef. The main phase of shallowing is recorded in the P3b and P4 Zones. Superimposed on the second-order trend, third-order cycles are recognized, and compared with regional sea level cycles reported from Egypt (Lüning et al., 1998; Speijer, 2003) and the global record. During the Danian the faunal assemblages restrict the paleodepth estimation to an outer neritic environment; the abundance of *G. beccariiformis* may indicate deposition at upper bathyal depths in the lower Subzone P1b. Within Subzone P1b (NP2) we suspect a temporary shallowing, based on the peak occurrence of inner neritic *Kenleyia* spp. and the decrease of deeper-water benthic taxa. However, the S/D ratio does not reflect a shallowing, and as
there is only an approximate correlation to the sequence boundary Da3 (Hardenbol et al., 1998), this shallowing might represent a local phenomenon or not a real shallowing. During the middle Paleocene, at the Subzones P3a-P3b transition a sea-level fall can be identified in our data. The reduced thickness of Subzone P3a suggests that a stratigraphic gap marks the boundary between Subzones P3a and P3b. This gap can be correlated to sequence boundary Sel1. A sea-level lowering was previously inferred on the basis of the ostracode record (Donze et al., 1982) and was observed elsewhere in Tunisia (Donze et al., 1982; Saint-Marc and Berggren, 1988). A similar sea-level fluctuation has been described in Subzone P3a at different locations in Egypt (Lüning et al., 1998; Speijer, 2003) and in western Europe by Hardenbol et al. (1998).

From Subzone P3b onwards all evidence is in favour of a regressive trend. The total magnitude of the shallowing is obscured by the interaction with the eutrophication signal, but is estimated to be some 150 m (from ~200 to ~50 m depth). The Frondicularia phosphatica bed at the base of Zone NP6 can be correlated with the Sel2 sequence boundary of Hardenbol et al., (1998) and with unconformities in eastern Egypt (Lüning et al., 1998; Speijer and Schmitz 1998). A correlation with the Thanetian sequence boundaries of Zones P4 and NP7/8 (Hardenbol et al., 1998) cannot be confirmed; although the level where the benthic assemblages are dominated by agglutinated taxa (i.e. Haplophragmoides spp.) can be tentatively correlated to Th2.

Higher resolution studies are needed to better constrain the timing of sea-level fluctuations and to improve the correlation with sequences elsewhere in North Africa and Europe.

Conclusions

The integrated paleoecological analysis of quantitative distribution patterns of Paleocene organic-walled dinocysts and benthic foraminifera from the El Kef section (NW Tunisia) allows a better understanding of the evolution of the Paleocene paleoenvironment. Our records indicate that from an initially oligotrophic, open marine, outer neritic to upper bathyal setting the environment evolved towards a more eutrophic inner neritic setting, influenced by coastal upwelling by the end of the Paleocene. Lower and middle Paleocene sediments were deposited in an outer neritic to uppermost bathyal environment at ~200 m depth. A long-term shallowing toward an inner neritic environment set in at the base of planktic foraminifera Subzone P3b and continued in Zone P4. The total magnitude of the shallowing is obscured by the interaction with the eutrophication signal, but is estimated to be some 150 m (from ~200 to ~50 m) and occurred in discrete cycles of which several can be correlated throughout the Southern Tethyan margin and to the eustatic curve of Hardenbol et al. (1998). During the late Paleocene intensified upwelling is inferred to explain increased productivity, leading to eutrophication of the water column and oxygen deficiency at the sea floor.
Acknowledgments

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Appendix I

The taxonomy of dinocysts is in accordance with Williams et al. (1998). The establishment of dinocysts groups implying similar paleoecological conditions is mainly due to the occurrence of certain genus related to certain environmental conditions, based on literature data (see Sluijs et al., 2005; Pross and Brinkhuis, 2005).

Areoligera group
This group includes inner neritic and coastal skolochorate dorsally-ventrally compressed Gonyaulacoid taxa, such as Areoligera spp. and Glaphyrocysta spp. (Brinkhuis and Zachariasse, 1988; Brinkhuis, 1994).

Cerodinium group
This group includes cavate Peridinioid cysts, such as Cerodinium spp., Paleocystodinium spp., Spinidinium spp. and Senegalium spp. Cerodinium is morphologically extremely similar to Deflandrea, which are neritic to ocean heterotrophic cysts (Sluijs et al., 2005). High abundance of Senegalium is associated with elevated nutrients (Brinkhuis and Zacharias, 1988).

Fibrocysta group
This group includes fibrous proximate to chorate gonyaulacoid cysts such as Fibrocysta spp. and Kenleyia spp., which are the most abundant taxa in this record, together with Cordospheridium spp., Operculodinium spp., Carpatella spp., Damassadinium californicum and Cribroperidiunium spp., which show very low abundances. These taxa generally characterized inner neritic environment (Brinkhuis, 1994; Brinkhuis et al., 1994; Powell et al., 1996; Sluijs et al., 2005; Pross and Brinkhuis, 2005).

Impagidinium spp.
Proximochorate Gonyaulacoid cysts. In recent environments Impagidinium is characteristic of open marine oligotrophic settings (Brinkhuis and Zacharias, 1988; Dale, 1996; Crouch et al., 2003; Piasecki, 2003).
**Lejeunecysta group**
This group includes proximate acavate (or weakly cornucavate) protoperidinioid cysts. This group is typical of high productivity areas (Brinkhuis et al., 1998; Pross and Schmiedl, 2002; Sangiorgi et al., 2002; Roncaglia, 2004).

**Spiniferites group**
This group includes *Spiniferites* spp. and *Achomosphaera* spp., cosmopolitan proximochorate Gonyaulacoid cysts (Brinkhuis, 1994; Brinkhuis et al., 1994; Pross, 2001; Sluijs et al., 2003).
Plate 1

Organic dinocysts

1. *Paleocystodinium* sp., sample AFN 615 (K48/1)
2. *Lejeunecysta* sp., sample AFN 621 (L43/4)
3. *Areoligera* sp., sample AFN 629 (K42/4)
4. *Cerodinium* sp., sample AFN 615 (E41/3)
5. *Cerodinium* sp., sample AFN 615 (K44)

Benthic foraminifera

6. *Bulimina cf. strobila* AFN 636
7. *Bulimina midwayensis*, sample AFN 619
8. *Cibicidoides pseudoacutus*, sample AFN 615
9. *Haplophragmoides* sp., sample AFN 636
10. *Anomalinoidea rubiginosus*, sample AFN 617
11. *Gavelinella beccariiformis*, sample AFN 599
Plate 1
References


CHAPTER III

Paleoenvironmental change at the Danian-Selandian transition in Tunisia: planktic foraminifera and organic-walled dinoflagellate cysts records

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Abstract

In the present study, we document paleoenvironmental change across the Danian-Selandian transition (61-59 Ma) in NW Tunisia. Diversification of Paleogene planktic foraminifera with the evolution of muricate and photosymbiotic lineages *Acarinina*, *Morozovella* and *Igorina* is recorded during this interval. The present study aims to understand early Paleogene geobiosphere changes in the southern Tethys, analyzing the evolution of surface water conditions.

Three localities were investigated: Ain Settara, Elles and El Kef, all representing outer neritic deposition. Paleoenvironmental changes are explored by combining planktic foraminiferal and organic dinocysts assemblages and relative proxies (planktic/benthic ratio, numbers of planktic foraminifera per gram, peridinioid/gonyaulacoid ratio; terrestrial/marine ratio). In addition, also geochemistry proxies (carbonate content and stable isotopes) are examined.

Our records indicate that the environment evolved from an initially oligotrophic, open marine, outer neritic setting in Zone P2-P3a towards a shallower and nutrient-rich setting from the base of Subzone P3b. This change is marked by a sudden change in organic-dinocyst assemblages, characterized by a peak of P-cysts (*Cerodinium* and *Lejeunecysta*), and an upwards decrease in deeper benthic taxa. Associated to these dinocysts assemblages, the lowest occurrence of *Apectodinium* is recorded suggesting environmental perturbations. However, this P-cysts peak is not associated to change in the planktic foraminiferal assemblages.
1 Introduction

The early Paleogene may be regarded as the warmest episode of the past ~ 100 million years. (i.e. Zachos et al., 2001; Wing et al., 2003; Zachos et al., 2003). Following the Cretaceous/Paleogene perturbation, the middle Paleocene (Danian-Selandian transition) is characterized by a first step of global warming. This warmth culminated during the earliest Eocene in a brief, super-greenhouse period, known as Paleocene/Eocene thermal maximum (PETM; Zachos et al., 2003).

In comparison with the PETM, the lower – middle Paleocene, or Danian-Selandian (D/S) transition (~61-59 Ma) is a poorly studied interval of the geological record, but interest is reviving. For example, recent studies indicate that the D/S transition was a time of marked global change, e.g. reflected in turnover of planktic foraminifera. Evolutionary novelties include evidence of increasing habitat stratification in the water column related to the acquisition of symbiotic-partnerships as a trophic strategy (Quillévéré and Norris, 2003). Subbotinids and globanomalinids probably preferred living within or below the thermocline, whereas acarininids, morozovellids and igorinids inhabited the surface mixed-layer (Shackleton et al., 1985; Pearson et al., 1993; D’Hondt et al., 1994; Van Eijden, 1995; Kelly et al., 1996; Lu et al., 1998; Quillévéré and Norris, 2003). Probably most morozovellids, acarininids and igorinids hosted photosymbionts, which may have facilitated these taxa to thrive in low-nutrient water masses (D’Hondt et al., 1994; Norris, 1996; Berggren and Norris, 1997; Quillévéré and Norris, 2003). In addition, the renewed interest for this time interval is also the result of studies defining the stage boundaries of the Paleocene (e.g., Berggren, 1994; Schmitz, 1994). Many of these studies were conducted in the Tethyan Realm, portraying biotic (Brinkhuis et al., 1994; Arenillas and Molina, 1995; Arenillas and Molina, 1996; Speijer, 2003) and geochemical changes (Schmitz et al., 1998) across this interval. Well-exposed, continuous, and now classic sections in Tunisia have played a central role in this research. Yet, compared to the studies on the Cretaceous/Paleogene boundary (e.g. Brinkhuis and Zachariasse, 1988; Keller, 1988; Adatte et al., 2002; Galeotti and Coccioni, 2002; Gardin, 2002; Luciani, 2002; Peryt et al., 2002), the Paleocene and, in particular, the D/S transition in Tunisia has been somewhat neglected. (e.g. Aubert and Berggren, 1976; Salaj et al., 1976; Peypouquet et al., 1986; Saint-Marc and Berggren, 1988; Brinkhuis et al., 1994; Kouwenhoven et al., 1997; Steurbaut et al., 2000).

The present study is part of a broader research effort, aiming to understand early Paleogene geo-biosphere changes as reflected in the southern Tethyan realm. Here, we report on biotic changes recorded in foraminifera and dinoflagellates across the D/S transition at three localities in NW Tunisia, Ain Settara, Elles and El Kef.

During the early to middle Paleocene, these successions were deposited on the continental margin at shallow outer neritic (Ain Settara) to deep outer-neritic (Elles and El Kef) depths. In chapter II an overview of broad paleoenvironmental changes, involving mainly
paleoproductivity and paleodepth, during the Paleocene (Zones P1b to P4) at El Kef is provided, by combining organic-walled dinoflagellate cysts (dinocysts) and benthic foraminiferal assemblages. It was concluded that the environment at El Kef evolved from an oligotrophic, open marine, outer neritic to upper bathyal setting during the early Paleocene towards a more eutrophic inner neritic setting, influenced by coastal upwelling during the late Paleocene. In particular, it was suggested that the onset of this environmental shift took place across planktic foraminifera Subzones P3a-P3b, during the D/S transition (Chapter II).

Here, we focus on the D/S transition in more detail, analyzing the evolution of surface water conditions across an ancient Tethyan onshore-offshore transect at three different localities, again by combining quantitative planktic foraminiferal and dinocyst records. In addition, a qualitative evaluation of benthic foraminiferal assemblages provides gross paleobathymetric estimates. Furthermore, some geochemical parameters (carbonate content and stable O, C isotopes) are investigated in order to potentially enhance the stratigraphic framework.

2 Danian and Selandian Stages

In the type region, Denmark, the D/S boundary is marked by an unconformity, between the limestones of Danskekalk Formation and the greensands and marls of the Lellinge Formation (Thomsen and Heilmann-Clausen, 1985). The time span included in this hiatus is poorly constrained (Thomsen, 1994), because the standard nannoplankton markers of low and middle latitudes for delineating NP4 and NP5 (respectively *E. macellus* and *F. tympaniformis*) are missing (Thomsen and Heilmann-Clausen, 1985). Based on data from Gemmas Allé (Denmark), Stouge et al. (2000) assigned the uppermost Danian to the Chiasmolithus bidens Subzone D10 sensu Perch-Nielsen (1979), comparable to part of Zone NP4 (Martini, 1971). The Selandian was assigned to the Toweius selandianus Subzone S2 sensu Perch-Nielsen (1979), equivalent to Zones NP4/NP5 (Martini, 1971) and which include the presence of Neochiastozygus perfectus. Moreover, Stouge et al., (2000) assume that based on planktic foraminifera the D/S hiatus corresponds approximately to Zone P2 (sensu Berggren et al., 1995).

The Danian and Selandian stages are chronostratigraphically equivalent to the lower Paleocene and the lower upper (“middle”) Paleocene, respectively. The boundary between these stages is delineated in different ways, using various criteria. Berggren (1994) and Berggren et al. (1995; 2000) proposed to correlate the D/S boundary with the P2/P3 zonal boundary, with an estimated age of 60.9 Ma, whereas Hardenbol et al. (1998) estimated the age for sequence boundary Sel 1 in Western Europe at 60.7 Ma (within lower Subzone P3a). Schmitz et al. (1998) studied the Zumaya section in northern Spain and suggested to define the base of the Selandian at a level close to LO of *F. tympaniformis* thus just below the zonal boundary between calcareous nannoplankton Zones NP4 and NP5. In Egypt and Jordan, we reported on a brief biotic and sedimentary event, termed the “Neo-duwi event”, within the
D/S transition (Chapter IV). This event is located within basal Zone P3b, near the top of Zone NP4, between the respective Lowest Occurrences (LOs) of *Fasciculithus* spp. (59.9 Ma based on Berggren et al., 1995) and *F. tympaniformis* (59.7 Ma based on Berggren et al., 1995).

**3 Geological setting and lithology, NW Tunisia**

The successions at Ain Settara, Elles and El Kef (NW Tunisia) are located at the southern margin of the Tethys. During the late Mesozoic and early Cenozoic, Tunisia was bathed by shallow seas, and by the end of the Cretaceous, the Jeffara and Kasserine Islands emerged in southern and central Tunisia. Kasserine Island separated a basin in the north from a narrow basin in the south. The studied localities (Fig. 1) were part of the northern basin known as the Tunisian Trough (Burollet, 1956; Salaj, 1980; Bobier et al., 1991; Burollet, 1991). The successions are dominated by hemipelagic marl-shale sedimentation, but with significant terrigenous input from Kasserine Island, and intermittent influx from emerged land located to the west (Adatte et al., 2002). Due to the high subsidence rate and sediment input, the Paleocene sequence in the Tunisian Through reaches up to 500 m thickness, decreasing towards Kasserine Island (Zaier et al., 1998).

![Fig. 1 Location map of the studied localities](image)

The three studied localities expose the El Haria Formation, spanning the Maastrichtian to lower Ypresian, and mainly consisting of brown-grey homogeneous marls and shales (Burollet, 1956). It overlies the chalky limestones of the Campanian/lower Maastrichtian Abiod Formation, and is overlain by the limestones of the Ypresian Metlaoui Formation (Burollet, 1956; Said, 1978). At Ain Settara, the Danian-Selandian transition contains a
series of thin indurate chalky marl beds (~18 m). A 50 cm thick glauconitic marl bed is present in the upper part of this interval. In the middle to upper part of the studied section, the marls become more shaley, and the indurate beds disappear. The Danian-Selandian succession at Elles is more monotonous, consisting in the lower part of homogeneous grey marls, becoming darker and more shaley in the upper part. Similar monotonous marls characterized the studied interval at Kef, becoming more shaley in Subzone P3b. At El Kef, a 9 m thick interval within the D-S transition (Subzone P3b) was not exposed (Kouwenhoven et al., 1997).

4 Material and Methods

Samples from Ain Settara and Elles were collected in November 2002 from trenches and holes at 20-30 cm depth below the weathered surface. Samples were collected every ~2 m at Ain Settara and ~1 m at Elles. Only the lower-middle Paleocene parts of these sections are evaluated here. Dinocyst data from El Kef (Chapter II) are also included in addition to planktic foraminiferal assemblages across the lower-middle Paleocene. Samples for foraminiferal studies were processed at Bremen University following standard micropaleontological procedures. They were dried in a stove at 60°C for at least 24 hours. About fifty gram of dry rock was soaked in soda (60g/l Na₂SO₄). When soda was not sufficient to break down the samples, Rewoquat (CH₃OSO₃⁻) was used. After disintegration, the samples were washed, and sieved over three sieves of 630, 125 and 63 µm mesh size, respectively. The fraction >125µm was used for our studies.

Qualitative distributions of benthic and planktic foraminifera have been determined. Planktic foraminifera were studied, counting 200-300 specimens classified at genus level, based mainly on Berggren and Norris (1997) and Olsson et al. (1999). The census counts were used to determine the percentage of planktics in the foraminiferal association (P/B ratio, expressed as 100xP/(P+B), cf. Van der Zwaan et al., (1990). The number of planktic foraminifera per gram of dry sediment is expressed as the planktic foraminiferal number (PFN).

Biostratigraphic studies on planktic foraminifera and on calcareous nannoplankton have been carried out. Calcareous nannoplankton has been studied qualitatively on smear-slides prepared following standard procedures. Rock samples of El Kef were not weighed prior to processing, thus the calculation of planktic foraminiferal numbers was not possible. Benthic foraminifera have been studied qualitatively, with the exception of El Kef, of which a quantitative benthic record has been published previously (Kouwenhoven et al., 1997; Chapter II).

The samples used for organic dinocysts studies were processed according to standard palynological techniques (c.f. Brinkhuis et al., 2003). The residues were sieved using a 10µm mesh-sieve, and prepared on slides using glycerin jelly. Palynomorphs were subdivided in seven categories (i.e. bisaccate pollen, other pollen and spores, acritarchs, determinable
dinocysts, *Pterospermella* spp., indeterminable dinocysts, and inner walls of foraminifera, if more than 3 chambers are encountered). Non-saccate pollen and spores are identified and grouped together as terrestrial palynomorphs. Dinocysts were counted up to 200 determinable cysts where possible. Frequencies of dinocysts are calculated relative to the total numbers of identifiable cysts. Dinocyst taxonomy is in accordance with that cited in Williams et al. (2004). In order to obtain the main variations of the paleoecological signal along the succession, the taxa have been grouped based on their broad paleoecological characteristics (see e.g., Sluijs et al., 2005; chapter II). The upper part of Ain Settara (samples ASP 19-21, and ASP12) did not yield any palynomorphs.

Total carbonate contents (CaCO\textsubscript{3}%) were measured on homogenized samples using the Scheibler method in the laboratory of sedimentary analysis of the Free University of Amsterdam. Stable isotopes (\(\delta^{13}C\) and \(\delta^{18}O\)) on whole-rock carbonate on Elles were performed in the department of Paleoecology and Paleoclimatology, Free University of Amsterdam, and on Ain Settara in the Department of Geosciences, Bremen University.

5 Biostratigraphy

The studied interval spans planktic foraminifera Zone P2, Subzone P3a and part of Subzone P3b (Berggren et al., 1995), corresponding to calcareous nannoplankton Zone NP4 (Martini, 1971) (Fig. 2).

5.1 Planktic foraminifera

Planktic foraminifera Zone P2, defined as the interval between the First Appearance Datum (FAD) of *Praemurica uncinata* and the FAD of *Morozovella angulata* (Berggren et al., 1995), spans ~12.5 m at Ain Settara and Kef, and 5.5 m in Elles. Zone P3 is defined as the biostratigraphic interval between the FAD of *Morozovella angulata* and the FAD of *Globanomalina pseudomenardii*. Zone P3 is usually subdivided into Subzones P3a and P3b based on the FAD of *Igorina albeari*. The base of Zone P3a can be traced in every locality, but the top part is obscured by a hiatus, which occurs at the P3a/b boundary at all localities. Subzone P3a spans ~3 m at Ain Settara and Elles, and ~7 m at Kef. Subzone P3b is more expanded: >20 m at Ain Settara, ~11 m at Elles, and ~15 m at Kef. The base of Zone P4 was recognized at Elles and at Kef, but not at the studied outcrop of Ain Settara, where a fault contact separates the Ypresian limestones of the Metlaoui Formation from Subzone P3b (note that other successions near Ain Settara show a complete upper Paleocene to lower Eocene succession; Steurbaut et al., 2000).

In the Middle East (Chapter IV), the identification of the P3a/P3b subzonal boundary on the basis of the lowest occurrence (LO) of *I. albeari* is problematic. Similar problems are also identified in Tunisia. Typical specimens of *I. albeari* rarely occur and only at higher stratigraphic levels. Therefore, we identify the base of Subzone P3b on LO of slightly keeled *Igorina* in assemblages with abundant and well-diversified *Morozovella*, including *M. aequa*.  

58
The LO of the latter taxon in ocean deposits is described from Zone P4 upwards (Olsson et al., 1999), but in the Tethys it occurred near the base of Subzone P3b.

Fig. 2 Stratigraphy of the studied localities. Planktic foraminifera biostratigraphy is based on Berggren et al. (1995), calcareous nannofossils biostratigraphy on Martini (1971).
5.2 Calcareous Nannofossils

Calcareous nannofossil Zone NP4 (Martini, 1971) is defined by the FAD of *Ellipsolithus macellus* (base) and by the FAD of *Fasciculithus tympaniformis* (top). We consider the first occurrence of *Fasciculithus* an important biostratigraphic event, occurring in the upper part of Zone NP4, calibrated at 59.9 Ma following Berggren et al. (1995).

At Ain Settara, the LO of *Fasciculithus* is recorded at the glauconitic marker bed (ASP10), which is equivalent to the glauconitic bed described by Steurbaut et al. (2000). In the more continuous Ain Settara succession studied by Steurbaut et al. (2000) the base of NP5 is situated ~30 m above the LO of *Fasciculithus* spp. At Elles the LO of *Fasciculithus* occurs in sample ELS10, and the LO of *F. tympaniformis* is recorded in sample ELS26 (~13 m above the LO of *Fasciculithus* spp.).

In both localities, the LO of *Fasciculithus* coincides with the lowest sample in Subzone P3b. Following Berggren et al. (1995), the FAD of *Fasciculithus* is recorded just above the base of Subzone P3b (~0.1 myr younger than the FAD of *I. albeari*). This indicates that the basal part of Zone P3b is missing. The reduced thickness of Subzone P3a indicates that also the upper part of Subzone P3a is lost in a hiatus in all sections.

6 Results

6.1 Benthic foraminiferal assemblages

In planktic foraminifera Zones P2 and P3 at Ain Settara, diverse assemblages are recorded, composed of various Nodosarians, Textularians, *Anomalinoides* (*midwayensis, praeacutus, rubiginosus*), *Alabamina*, *Osangularia*, *Bulimina*, *Neoflabellina*, *Gyroidinoides*, and *Cibicidoides pseudoacutus*. *Anomalinoides affinis* and *A. susanaensis* occur only in the lower part. *Stainforthia* spp. is frequent within Subzone P3b.

In Elles in Zones P2 and P3a, the benthic assemblages are characterized by numerous neritic taxa as at Ain Settara, but including *Gavelinella beccariiformis* (a bathyal species) and *Aragonia, Globocassidulina subglobosa, Cibicidoides* spp., *C. midwayensis*. In lower Subzone P3b this assemblage persists, but *G. beccariiformis* disappeared.

6.2 Planktic foraminifera

In planktic foraminifera Zone P2–P3a, the assemblage is mainly composed of *Praemurica, Subbotina* and *Parasubbotina*, which together make up ~85% in Ain Settara (Fig. 3), between 80-90% in Elles and in El Kef (Fig. 4, 5). In particular, *Subbotina* and *Parasubbotina* are equally distributed between 30% and 40%. *Morozovella* and *Acarinina* already occur in P2 in very low numbers (<1%) and slowly increase up to <10% in Zone P3a, with highest numbers at Ain Settara. *Igorina* only occurs from the base of Subzone P3a in low numbers (<1%). *Chiloguembelina* occurs only in the background (~1%).
From Subzone P3b, above the unconformity, the planktic foraminiferal assemblages change. *Praemurica* disappears and, instead, *Morozovella* dominates the surface-dwelling taxa (~30%, ~50%, ~40% in Ain Settara, Elles and Kef, respectively). *Parasubbotina* and *Subbotina* are still well represented, although *Parasubbotina* slightly lower. Only in sporadic samples, these taxa abruptly decrease (in ASP18 both decrease; in AFN616 *Parasubbotina* decreases ~10%). Instead, at Elles, *Parasubbotina* generally decreases (10-20%). *Acarinina* and *Igorina* constitute a minor part of the surface dwellers (<10%). *Globanomalina* constantly ranges <15%, lower at Ain Settara (generally <10%). *Chiloguembelina* is generally poorly represented, somewhat more abundant (~2%) at Elles. *Zeauvigerina* occurs in several samples at Ain Settara, mainly in Subzone P3b (<3%), whereas this taxon is not found in the other localities.

![Fig. 3 Planktic foraminifera (in dark grey) and dinocysts (in light grey) assemblages at Ain Settara. The abundances are expressed in percentage.](image)

### 6.4 Palynology

Nearly all samples contain palynological assemblages dominated by marine palynomorphs (Figs. 3, 4). The results from Kef are also presented in Chapter II. The dinocyst taxa are placed in ecogroups as established in Chapter II.

In planktic foraminifera Zones P2- P3a, representatives of the *Spiniferites* group are the main component of the assemblage, up to 80% at Ain Settara and Elles. The *Fibrocysta* group is also quite abundant; up to 40% at Ain Settara, and even higher at Elles (60%). Abundances of the *Cerodinium* and *Areoligera* groups are <15%. Representatives of the *Lejeunecysta* group are almost absent (<1%). Indeed, with the exception of a peak (9%) at...
Elles in the lowermost part, the *Lejeunecysta* group is generally rare (<1%). Representatives of the oceanic *Impagidinium* group are almost absent at Ain Settara (except in sample ASP5, <1%), while they occur in low abundances at Elles and Kef (~1%).

From Subzone P3b onwards the assemblages start to diversify. At Ain Settara, at the distinct glauconitic bed, the assemblage is characterized by increasing *Fibrocysta* (~35%), *Cerodinium* (~35%, mainly *Isabelidium* spp.) and decreasing *Spiniferites* (<20%) groups.

![Fig. 4](image1.png)

**Fig. 4** Planktic foraminifera (in dark grey) and dinocysts (in light grey) assemblages at Elles. The abundances are expressed in percentage.

![Fig. 5](image2.png)

**Fig. 5** Planktic foraminifera assemblages at El Kef. The abundances are expressed in percentage.
Just above this bed, representatives of the *Cerodinium* group are still abundant (15%) and the *Lejeunecysta* group abruptly increases (~20%). From this level upwards, these taxa range through the entire Subzone P3b. The *Fibrocysta* group increases (<60%), while the *Spiniferites* group has generally lower abundances (<60%).

At Elles a major change is recorded ~1 m above the “base” of Subzone P3b (ELS 11), indicated by a peak of the *Cerodinium* group (~45%), and increased *Lejeunecysta* representatives (~10%), whereas the *Spiniferites* and *Fibrocysta* groups abruptly diminish (25% and 10%, respectively). Representatives of the *Microdinium* group sporadically occur, except for a peak of 7% in sample ASP17, and in various peaks at Elles, up to 30% in sample ELS14. The *Areoligera* group does not vary considerably (usually <10%). Relative numbers of the *Impagidinium* group remain low, except for a single peak of 3% (sample ELS13), with a concomitant peak of the *Spiniferites* group (35%). At Ain Settara (ASP11), the first occurrence of the *Apectodinium* group is recorded in this interval (2.4%). Up section, representatives of this group occur in several samples in low relative numbers, with the exception of a peak of 3% in sample ASP15. At Elles the LO of *Apectodinium* occurs in a younger sample (ELS14) as single occurrence, and is associated with a peak of the *Microdinium* (30%) and *Areoligera* groups (10%). At Kef, members of the *Apectodinium* group occur just above the unconformity in assemblage with high number of representatives of the *Cerodinium* and *Spiniferites* groups. Numbers of the *Lejeunecysta* group also increase at this level.

### 6.5 Paleoenvironmental proxies

#### 6.5.1 Foraminiferal proxies

In planktic foraminifera Zones P2-P3a, at Ain Settara, the planktic/benthic ratio fluctuates from 45% to 70% (Fig. 6), whereas at Elles, the P/B is constantly higher (80-90%). In Subzone P3b at Ain Settara a drop of the P/B (~33%) coincides with the glauconitic bed; above this level, values are generally more constant ~50%. Instead, little variation is recorded at Elles except for decreasing values in the uppermost studied interval (<65%).

At Ain Settara, the planktic foraminiferal number fluctuates between 200/g and 1,300/g in upper Zone P2, lower in Subzone P3a (<500/g). Similarly, at Elles, PFNs vary between 100 and 500/g in Zones P2-P3a, with a minimum value in the lower part of Zone P2 (<100/g).

Above the unconformity, in Subzone P3b, in Ain Settara the PFN values are lower than in P2-P3a (200-600/g), except a peak 1000/g in ASP12. Instead, an opposite trend characterizes Elles, where increased values are recorded (~3000/g). In the uppermost part of Elles these numbers decrease (<100/g), similar to the P/B ratio trend.
Fig. 6 The planktic/benthic ratio (P/B %), the number of planktic foraminifera/gram (P/N) expressed as logarithmic scale, the carbonate content (CaCO₃ %), the peridinioid/gonyaulacoid ratio, the terrestrial/marine palynomorph ratio, the oxygen and carbonate stable isotopes are plotted for each locality. PF – Planktic foraminifera biostratigraphy based on Berggren et al. (1995).

6.5.2 Palynological proxies

At every locality, the relative numbers of peridinioids (P/G ratio) are generally very low in Zones P2 and P3a. At Ain Settara, their numbers increase from the glauconitic bed upwards, where highest relative values occur. Further upwards, values are lower, but still higher than those in Zones P2 and P3a. Similarly, at Elles, a peak of peridinioids occurs in Subzone P3b, ~1 m above the occurrence of *Fasciculithus* and from this level upwards, the values are generally higher than in lower samples. At Kef, at the base of Subzone P3b a peak of P/G ratio is also described.

McCarthy and Mudie (1998) pointed out that the numbers of terrestrial palynomorphs in marine sediments decreases exponentially with distance to shore, thus they are useful in sea-level reconstructions. In the studied localities, the relative contribution of continentally derived organic material (S/D ratio) is always low; therefore, they cannot support sea-level
variation. As it was already pointed out for El Kef (Chapter II), these low S/D values might be related to the distance of the sedimentation area from the source of terrestrial input.

6.6 Geochemical proxies

6.6.1 Carbonate Content

The marls in planktic foraminifera Zones P2-P3a contain up to 50% CaCO₃ at Ain Settara, lower in Subzone P3b (between 20% and 40%). At Elles, the lower marls contain ~60% CaCO₃, decreasing to <40% in Subzone P3b, where the marls are more shaley.

Fig. 7 Planktic foraminiferal and organic dinocysts assemblages, planktic/benthic ratio (P/B %), number of planktic foraminifera/gram (P/N) expressed as logarithmic scale, carbonate content (CaCO₃ %), peridinioid/gonyaulacoid ratio and terrestrial/marine palynomorph ratio are plotted for each locality. PF – Planktic foraminifera biostratigraphy based on Berggren et al. (1995).
6.6.2 Stable Isotopes

In planktic foraminifera Zones P2-P3a, $\delta^{13}C$ values are low at the base of Ain Settara (-1.2‰), and slowly increase up to a maximum 0‰ (ASP7), and they are slightly lower (-0.3‰) in Subzone P3a. At Elles, $\delta^{13}C$ values are generally higher than at Ain Settara (-0.7‰ and 0.2‰), and they exhibit more fluctuations. In Subzone P3b, values are similar to those at Ain Settara. At Ain Settara, small positive peaks occur in sample ASP11 coinciding with increased peridinioid cysts and the lowest occurrence of Apectodinium, and one in sample ASP16 coinciding with increased Spiniferites and increased PFN (Fig. 6). At Elles, from the lowest occurrence of Fasciculithus upward, $\delta^{13}C$ values are generally constant (~0.2‰).

The $\delta^{18}O$ values range between -2.6‰ and -1.6‰ in Zones P2-P3a at Ain Settara, with a minimum value (-2.6‰) in ASP6. Similar values are recorded at Elles (-2.8‰ and -1.8‰), but they exhibit wider fluctuations.

In Subzone P3b, the values are similar. At Ain Settara, negative wiggles are recorded together with higher $\delta^{13}C$ (ASP11 and ASP16: -2.6 and -3.6‰, respectively). Such large fluctuations are probably indicative of diageneric overprinting.

7 Discussion

7.1 Paleobathymetric change

At Ain Settara, within Zones P2-P3a, the benthic foraminiferal assemblage and P/B ratios are indicative of shallow outer neritic (100-150 m) deposition. This is in agreement with the dinocysts being dominated by the shelf groups Spiniferites and Fibrocysta, and an absence of the typical offshore taxa Impagidinium spp. (Brinkhuis and Zachariasse, 1988; Crouch et al., 2003). At Elles, higher P/B ratios and deeper-water benthic foraminiferal taxa (i.e. Gavelinella beccariiformis) suggest a deeper outer neritic setting (150-200 m) in Zones P2-P3a, which is in agreement with the presence of Impagidinium. Outer neritic paleodepths in Zones P2-P3a were also inferred at El Kef (Chapter II).

At Ain Settara, at the conspicuous glauconitic bed, the benthic assemblage does not change, whereas the P/B decreases. In Subzone P3b, the disappearance of some deeper benthic taxa (A. affinis, A. susanaensis) together with a decreasing P/B ratio suggests a shallowing. This is also observed in the dinocyst assemblage, in which neritic taxa, in particular peridinioid cysts, became more abundant. We estimate that the paleodepth changed from 100-150 m in Zones P2-P3a to <100 m in Subzone P3b. Similarly, at the base of Subzone P3b at Elles, we find the disappearance of the bathyal taxon G. beccariiformis and an increase of peridinioid cysts, suggesting a shallowing from deep-outer neritic deposition (150-200 m) to shallow outer neritic deposition (100-150 m). A similar shallowing was also observed at Kef from Subzone P3a to Subzone P3b (Chapter II).
7.2 Paleoenvironmental conditions

7.2.1 Danian
The evolutionary trend of planktic foraminifera from spinose and praemuricate taxa towards assemblages dominated by muricate taxa (Norris, 1996; Kelly et al, 1996; Berggren and Norris, 1997; Olsson, 1999) is observed in the studied area. In planktic foraminifera Zone P2, spinose genera (*Subbotina* and *Parasubbotina*) and *Praemurica* dominate the assemblage. Already in upper Zone P2, the earliest specimens of *Morozovella* (*M. praeangulata*) and *Acarinina* (*A. praeequa*) are observed. Our data show that *Praemurica* survived up into Subzone P3a in the southern Tethys, as it was already described in Egypt and Jordan (Chapter IV). The decrease of this taxon corresponds to a gradual increase of *Morozovella*. In Zones P2-P3a, well-diversified planktic and benthic foraminiferal assemblages, dominance of Spiniferites and Fibrocysta in the dinocyst assemblages and low peridinioid/gonyaulacoid ratio suggest oligotrophic conditions at both localities (Fig. 7), in agreement with data from El Kef (Chapter II).

7.2.2 Selandian
The transition between Subzone P3a-P3b is marked by an unconformity, observed in every locality. The foraminiferal and palynological assemblages and proxies indicate paleoenvironmental change across the D/S unconformity, from the base of Subzone P3b onwards (corresponding to the change from sub-biofacies 3a to 3b described in El Kef in Chapter II).

At the base of Subzone P3b a thick glauconitic bed is present at Ain Settara, and at Elles glauconite grains are also abundant within the washed residue (ELS 10). Although the genesis of glauconite is poorly known, is generally, associated with slow deposition, under reducing conditions on the continental margin (often between 30-700m) and facilitated by presence of organic matter (Reading ed., 1986). Also in Denmark, the base of the Selandian is marked by glauconitic greensands and marls of the Lellinge Formation (Thomsen and Heilmann-Clausen, 1985).

Steurbaut et al., (2000) suggested that the glauconitic bed at Ain Settara could represent the transgressive phase of the sequence Sel-1. It was also suggested that the interval underneath this transgressive bed could represent a low stand deposit with channel incision into Danian high-stand deposits. Our faunal data (P/B ratio, benthic foraminifera and dinocysts) from this level, however do not support a low-stand below the glauconitic bed. Depositional depth was similar to the interval below. In our view the main unconformity is situated below the glauconitic bed and thus the Selandian transgressive deposits rest on top of Danian high-stand deposits. In our study at Kef, we also recognized a third order sequence boundary (Sel-1) at the base of Subzone P3b (Chapter II).

At these localities, above the base of Subzone P3b and the lowest occurrence (LO) of *Fasciculithus*, high numbers of peridinioid cysts (*Cerodinium* and *Lejeunecysta*) are recorded.
associated also with LO Apectodinium. Increased P-cysts are generally related to enhance primary productivity. In particular, as it was argued in Chapter II, increased heterotrophic/autotrophic ratio (P/G) based on protoperidinioid cysts (Lejeunecysta) is more reliable in the studied area and suggested higher nutrient availability. Moreover, at Elles, this peak corresponds to increased planktic foraminifera numbers suggesting increased productivity.

Above this change, during subzone P3b, a shallower, nutrient-rich environment succeeded the oligotrophic conditions of Zone P2-P3a. Accordingly, peridinioid cysts are more abundant; in particular, representatives of the Lejeunecysta group increased, whereas Spiniferites and Fibrocysta groups decreased. At Ain Settara the occurrence of the planktic Zeauvigerina suggests low oxygen conditions in the deeper water column as this genus belongs to the family Heterohelicidae (Olsson et al., 1999). The increase of Stainforthia in the benthic assemblage indicates low-oxygen levels also at the seafloor at Ain Settara. A shallower and more nutrient-enriched environment characterized Subzone P3b also at El Kef, where eventually eutrophic inner neritic conditions settled in the late Paleocene (Kouwenhoven et al., 1997; Chapter II). Overall, the Selandian in the study area is characterized by a higher productivity system both in the water column and on the seafloor than during the Danian.

7.3 First Occurrence of Apectodinium

In the uppermost Paleocene, a bloom of Apectodinium is globally recorded in association with the Paleocene-Eocene thermal maximum (Crouch et al., 2001). It has been suggested that this taxon preferred warm eutrophic inner neritic waters (Crouch et al., 2003). Brinkhuis et al (1994) reported the lowest occurrence (LO) of representatives of the genus from our study. We now record the FO of Apectodinium at Ain Settara at the base of Subzone P3b, associated with increased peridinioid cysts and a small positive shift of $^{13}$C. Also at Kef, it was recorded in lower Subzone P3b (Brinkhuis et al., 1994). It is striking that at each locality, the LO is associated with a peak of representatives of the Cerodinium group. This suggests relatively shallow marine conditions and increased nutrient supply (e.g Sluijs et al., 2005). Whilst in Kef, the LO is evidenced by only a single specimen, at Ain Settara it occurs in higher abundance. Instead, at Elles, Apectodinium, first occurs in a younger interval of Subzone P3b, and is associated with a peak of representatives of the Microdinium group; a group which usually occurs only in the background. Considering that the LO of Apectodinium in the outer neritic setting of Kef is recorded through the finding of a single specimen only, we suspect that its absence in coeval deposits at Elles is only related to the amount of analyzed material. The overall pattern further confirms the preference of Apectodinium for more inner neritic water masses, in which nutrient availability was probably higher.
Conclusions

Paleoecological and paleoenvironmental evaluation at the Danian-Selandian transition is documented by combining planktic foraminifera and organic dinocysts assemblages from Tunisia. The studied localities are located at the shallow-outer neritic (Ain Settara) and deeper-outer neritic (Elles and Kef) localities.

An open marine, oligotrophic setting characterized the lower Paleocene (Zones P2-P3a) as suggested in high numbers of *Spiniferites* and *Fibrocysta* and well-diversified benthic and planktic foraminiferal assemblages. Between Subzones P3a and P3b an unconformity marks all sections studied pointing to a eustatic or regional tectonic event. From lower Subzone P3b, the area shallowed and surface productivity increased, as suggested in the increased of P-cysts and decreased of deeper-water benthic foraminifera.

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Plate 1

Organic dinocysts

1. Apectodinium sp., sample ELS 52
2. Cerodinium sp., sample ELS 11
3. Areoligera sp., sample ASP 4
4. Lejeunecysta sp., sample AFN 621
5. Lejeunecysta sp., sample AFN 621
6. Pollen, sample ASP 18

Benthic foraminifera

7. Neoflabellina sp., sample ELS 13
8. Cibicidoides pseudoacutus, sample AFN 615
9. Gavelinella beccariiformis, sample KEF 599

Scale bar: 50µm

Planktic foraminifera

10. Subbotina triloculinoides, sample AFN 619
11. Globanomalina, sample ELS 13
12. Morozovella conicotruncata, sample ELS 13

Scale bar: 50µm
Plate 1
References


CHAPTER IV

Transient biotic change within the Danian- Selandian transition in Egypt and Jordan

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CHAPTER IV

Transient biotic change within the Danian- Selandian transition in Egypt and Jordan

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Abstract

A transient biotic change within benthic foraminiferal assemblages was previously documented in neritic deposits in Egypt spanning the Danian-Selandian transition. In the present study, we investigate associated stasis and change in planktic foraminiferal assemblages and whole-rock $\delta^{13}$C and $\delta^{18}$O records in five outcrops along a middle neritic to upper bathyal transect that stretches from Egypt (Gebel Duwi, G. Nezzi, G. Aweina G. Qreiya) to Jordan (Shaubak). The studied interval (61-59 Ma) records a main diversification phase of Paleogene planktic foraminifera with respect to the initiation of photosymbiosis as trophic strategy and the differentiation of depth habitats. In particular, the muricate lineages Acarinina, Morozovella and Igorina evolved successfully within this time interval.

In the study area, organic-poor shaley marls contain diversified planktic and benthic assemblages. These monotonous successions are interrupted by a dark organic-rich marl bed, with abundant planktic foraminifera and fish remains. Benthic foraminifera in this bed are rare, but consistently dominated (up to 60%) by Neoepiploides duwi, an inner-middle neritic species. Because of this transient anomalous occurrence, we term this the “Neo-duwi event”. At the same time, the planktic foraminiferal assemblages show two main patterns within the basin. In particular, increasing numbers of Acarinina and Parasubbotina characterize the Nile Valley localities (Aweina, Nezzi, and Qreiya), whereas minute Morozovella temporarily flourished at Duwi and Shaubak. These observations point towards two different paleoenvironmental settings within the basin, in relation to paleoceanographic and paleoclimatic changes. The patterns in the Nile Valley suggest stronger water column stratification due to enhanced freshwater input. In contrast, in the eastern part of the basin (Shaubak and Duwi), an upwelling system settled. Moreover, our results are compatible with a significantly different ecology between the symbiont-bearing genera Acarinina and Morozovella. Earliest Morozovella appears to have been less tolerant to lowered salinity, but better equipped to deal with enhanced nutrient levels. Considering the many biotic and sedimentological similarities between the “Neo-duwi event” and the Paleocene-Eocene Thermal Maximum in the studied basin, similar paleoenvironmental processes appear to have operated in this region during these two events. Consequently, it seems as if the “Neo-
**duwi event** could have resulted from a significant climatic event at the beginning of the long-term warming trend of the early Paleogene.

## 1 Introduction

The Paleogene has become appreciated as a climatically highly dynamic period, involving the transition from the near ice-free world of the Cretaceous to the glacially dominated world of the Neogene (Zachos et al., 2001). The apparent global warming trend during the Paleocene is associated with important biotic and environmental changes (Zachos et al., 2001; Wing et al., 2003; Zachos et al., 2003; Billups et al., 2004). Whereas numerous recent studies focus on the Paleocene/Eocene thermal maximum (PETM), the middle Paleocene is still poorly documented, in terms of paleoceanographic and climatic dynamics. The PETM may have been the most dramatic event within a series of brief warm periods known as hyperthermals in the late Paleocene to early Eocene (Thomas and Zachos, 2000; Bralower et al., 2002). Moreover, while ocean drilling has provided new insights into the characteristics of Paleocene oceans, ancient continental margins have received fairly little attention. The southern Tethyan margin represents an important area for studying processes on the Paleocene continental margin, as it provides numerous well-exposed outcrops, yielding well-preserved microfossils and representing a variety of paleoenvironmental settings.

The early middle Paleocene is considered an important period for the evolution of Paleogene planktic foraminifera from flattened globigerine forms via turborotalids to globorotalids (Cifelli, 1969). A phase of radiation, as indicated by increasing species diversity and diversification of muricate taxa (morozovellids, acarininids, igorinids), mainly occurred during the late Danian to early Selandian (Lu and Keller, 1995; Kelly et al., 1996a; Norris, 1996; Arenillas and Molina, 1997; Berggren and Norris, 1997; Olsson et al., 1999; Quillévéré and Norris, 2003). Moreover, the end of the Danian is marked by an increase in depth stratification of planktic foraminifera (Quillévéré and Norris, 2003) and the simultaneous acquisition of photosymbiotic algae within muricate taxa could represent an evolutionary novelty within planktic foraminifera (D’Hondt et al., 1994; Norris, 1996; Quillévéré and Norris, 2003).

In Egypt, monotonous marls and shales of the Paleocene Dakhla Formation are interrupted by a peculiar dark-brown shaley-marl bed within the Danian-Selandian transition. This bed rich in organic carbon and fish remains shows anomalous foraminiferal assemblages, strongly dominated by muricate taxa (Speijer, 2003). The foraminiferal assemblages are also characterized by very high planktic/benthic (P/B) ratios (~99%). Because of the dominance of *Neoeponides duwi* among the benthic taxa, we coin this level the “Neo-duwi event”. Sedimentological and microfossil characteristics suggest that the “Neo-duwi event” bed was deposited during rapid sea-level rise after a lowering phase Speijer (2003), during a period, which lasted probably less than 200 ky.
In this work, we expand on previous results from Egypt (benthic foraminifera, P/B ratios, carbonate content and total organic carbon), by extending the working area to Jordan and including planktic foraminifera assemblages and whole-rock stable isotope results. In this way, we explore possible paleoceanographic scenarios and causes of the “Neo-duwi event”. Our results point towards variations in productivity in relation to paleoceanographic and paleoclimatic changes. Considering the many biotic and sedimentological similarities between the “Neo-duwi event” and the PETM, similar paleoenvironmental processes appear to have operated regionally during these two events. Consequently, we speculate that a hyperthermal may have occurred during the Danian-Selandian transition. Detailed research on middle Paleocene records elsewhere is needed to further explore this idea.

2 Geological setting

We studied six sections that are located along the Nile Valley (Gebel Aweina, Gebel Nezzi, Gebel Qreiya), Red Sea coast (Gebel Duwi) and in central West Jordan (Shaubak and Gebel Qurtayssiat) (Fig. 1). The hemipelagic sediments studied were deposited in an epicontinental basin on the north-western margin of the Arabian-Nubian shield (Bartov and Steinitz, 1977; Said, 1990). Tectonically, the late Mesozoic and Paleogene of Egypt can be subdivided into two major provinces, the stable shelf in the south (also known as Nile Basin) and the unstable shelf in the north (Syrian Arc), (Said, 1990; Shahar, 1994). Deposition of hemipelagic sediments was controlled by this tectonic regime that has probably been active since the late Cenomanian (Al Rifaiy and Cherif, 1987; Bauer et al., 2003). All localities studied are situated on the stable shelf (Said, 1990; Youssef, 2003).

![Fig. 1](source: GEBCO) Location map of the studied area. During the Neogene, the Jordanian localities shifted ~100 km north in response to sinistral movements along the Dead-Sea transform fault (DST) (Garfunkel and Ben-Avraham, 1996).
Shaubak and Gebel Qurtayssiat, located ~40 km south and southeast of the town of Tafilah, respectively, are situated in a basin that experienced tectonic instability because of its vicinity to the Syrian Arc (Abed and Amireh, 1999; Kuss et al., 2003; Schulze et al., 2003). Within the studied time interval, the sections are arranged along a paleobathymetric transect, generally deepening in a NNW direction (Speijer, 2003). At Gebel Duwi, deposition took place at middle to outer neritic paleodepths (70-150 meters), while the Aweina, Qreiya, Nezzi and Qurtayssiat sections represent the outer shelf (150-250 meters) of the depth transect (Speijer, 2003). Shaubak represents an upper bathyal (250-300 m) conditions, based on mixed Midway and Velasco type benthic foraminiferal assemblages (Berggren and Aubert, 1975), yielding common *Gavelinella beccariiformis* and rare *Nuttallides truempyi*.

### 2.1 Lithology and lithostratigraphy

In Egypt, the Danian and Selandian Stages are represented by the upper part of the Maastrichtian-Paleocene Dakhla Formation (Said, 1990), which consists of monotonous brownish to grey marls and shales, with intercalated thin limestone beds (Fig. 2). It is overlain by limestones and chalks of the Thanetian Tarawan Formation. Sediments of the Dakhla Formation accumulated in an inner to outer shelf environment (Hendriks, 1987). The yellow to grey chalky marls and marls of the Danian-Selandian interval in Jordan belong to the Muwaqqar Chalk Marl Formation (MCM; (Masri, 1963). This formation is overlain by the chert-rich chalky limestones of the Ypresian Umm Rijam Formation.

In all studied sections, except Gebel Qurtayssiat, the monotonous marly intervals are interrupted by the “Neo-duwi event” bed, a darker bed (up to 1 m thick), which is more shaley, partially laminated, rich in fish remains, and contains common to abundant *Neoeponides duwi* (Fig. 2). In Shaubak, this bed is situated only 5.8 m below the contact with the Eocene Umm Rijam Formation, indicating an expanded hiatus in the upper Paleocene.

### 3 Material and Methods

Sample spacing is about one meter for most sections, except for Aweina, where an 8-m thick interval across the Danian-Selandian transition has been sampled with a higher resolution (on cm to dm scale).

Standard micropaleontological procedures have been used to process the samples for foraminiferal studies. Rock samples were dried in a stove at 60°C for at least 24 hours. About fifty grams of dry rock were soaked in soda (50g/l Na₂SO₄). Whenever repeated soda processing was not sufficient to break down the samples, the tenside Rewoquat (CH₃OSO₃⁻) was used. After disintegration, each sample was washed over a 63-μm mesh size and dry-sieved over sieves of 630 μm and 125 μm mesh size, respectively. The fraction 125-630 μm was used for foraminiferal studies. Rock samples of Gebel Aweina, Gebel Duwi and Shaubak
were weighed prior to processing, enabling the calculation of numbers of planktic foraminifera per gram of dry sediment.

Qualitative distributions of benthic and planktic foraminifera have been determined. Planktic foraminifera have also been studied quantitatively, by counting 200-300 specimens classified at genus level, using the taxonomic concepts of Berggren and Norris (1997) and Olsson et al. (1999).

Fig. 2 Schematic sketch of the sections: biostratigraphy and lithology. PF – planktic foraminifera biozones, based on Berggren et al. (1995). CNP – calcareous nannoplankton Zones based on Martini (1971). The localities are arranged along bathymetric transect from upper bathyal (north-east) to middle neritic (south-west). The horizontal bar correlates the “Neo-Duwi event”.

81
The census counts were used to determine planktic/benthic ratios (expressed as 100xP/(P+B)), which have been used to estimate paleobathymetry or as paleoproductivity index (Berger and Diester-Haass, 1988; Van der Zwaan et al., 1990). Biostratigraphic studies on planktic foraminifera and on calcareous nannoplankton were carried out. Calcareous nannoplankton biostratigraphy has been determined from standard smear-slides on the sections of Shaubak (21 samples), Aweina (41 samples), Qreiya (22 samples) and Qurtayssiat (22 samples). The frequency of calcareous nannofossils has been evaluated on two/three vertical traverses. Samples from Qurtayssiat have not been used for further interpretations, due to a hiatus across the Danian-Selandian transition. We refrain from using an age model for representing our data, because of the various biostratigraphic complications encountered. Moreover, intervals of slight to severe dissolution are found bracketing the “Neo-duwi event” in the Nile Valley. In these intervals, the biostratigraphy is poorly constrained. Total carbonate content (% CaCO₃) was measured on homogenized samples from Shaubak using the Scheibler method at the Free University of Amsterdam. For Gebel Nezzi and Gebel Qreiya the data were obtained from Speijer (2003). Together, the number of planktic foraminifera per gram, the P/B ratio, and the carbonate content enable us to evaluate marine productivity and post-depositional changes of the assemblages.

Whole-rock stable isotopes (δ¹³C and δ¹⁸O) were analyzed at the Free University of Amsterdam (Qreiya and Nezzi), Bremen University (Shaubak), Göteborg University (Qurtayssiat and Aweina). We chose to analyze stable isotopes on whole rock instead of planktic foraminifera, because in the Paleocene deposits from Egypt these are generally strongly recrystallized and in-filled by diagenetic calcite, prohibiting their usage (Schmitz et al., 1996). Because of logistic problems during the course of these studies, it was not possible to process the samples in just one laboratory.

4 Biostratigraphy

The studied interval spans planktic foraminifera Zones P2 to P3 (Berggren et al., 1995), corresponding to calcareous nannoplankton Zones NP4 to NP5 (Martini, 1971) (Fig. 2).

4.1 Planktic foraminifera

Planktic foraminifera Zone P2, defined as the interval between the First Appearance Datum (FAD) of Praemurica uncinata and the FAD of Morozovella angulata, (Berggren et al., 1995), measures between 8 m thickness at Duwi to 3 m at Qreiya and Shaubak. Zone P2 was not sampled within the current detailed dataset of Aweina, but it measures about 10 m (Speijer and Schmitz, 1998). Zone P3 is defined as the biostratigraphic interval between the FAD of Morozovella angulata and the FAD of Globanomalina pseudomenardii. The thickness of this zone varies from 13 m (Nezzi), ~12 m (Shaubak and Qreiya) to ~5 m in Duwi. In Aweina
Zone P3 measures ~20 m; the middle 8 m are considered in this work. The base of this zone can be traced in every locality. Within this zone, the identification of Subzones P3a and P3b, defined by the FAD of *Igorina albeari*, appears more problematic in this area than previously realized. At Shaubak and Duwi, from ~1 m below the “Neo-duwi event” bed, and within this bed, the planktic foraminiferal assemblage is characterized by an abundance of typical *Morozovella angulata*, *M. conicotruncata* and *Igorina pusilla*. The occurrence of these taxa is described from the base of Zone P3a in the oceans (Berggren et al., 1995; Berggren and Norris, 1997; Berggren et al., 2000; Quillévéré et al., 2002). Rare specimens of *I. tadjikistanensis* and *M. aequa* are also found in these assemblages, which indicate a younger age in oceanic records (respectively in P4 and P3b, Berggren and Norris, 1997). This indicates either an early appearance of these taxa in our records, or a delayed appearance of *I. albeari*. Specimens of *Igorina*, which start to develop a keel, like in *I. albeari*, are also found. Even though a typical *I. albeari* does not occur, we suggest that this is a typical assemblage indicative of planktic foraminifera subzone P3b (M. R. Petrizzo and I. Premoli Silva, 2003, pers. comm.). Why *I. albeari* is absent at this level is not clear.

A similar situation is found at Nezzi, Aweina, and Qreiya, but the definition of the P3a/P3b subzonal boundary is even more problematic, because of a scarcity of planktic foraminifera across this event. In the studied sections *I. albeari* first appears above the “Neo-duwi event”. The absence of a well-defined *I. albeari* explains why previously, the “Neo-duwi event” was considered to be situated within the top of Subzone P3a (Speijer, 2003).

It is well known, that in the study area typical, distinctly keeled, specimens of *Globanomalina pseudomenardii*, the marker of planktic foraminifera Zone P4, is rarely found (Speijer et al., 2000). Therefore, the base of Zone P4 is approximated by the lowest occurrence of *Morozovella velascoensis*, as previously adopted in this area (Speijer, 2003). In Tunisia (at Ellès), the lowest occurrence of *M. velascoensis* coincides with the lowest occurrence of *G. pseudomenardii*, suggesting that in the Southern Tethys the lowest occurrence of *M. velascoensis* is a good approximation of the base of Zone P4 (pers. observ.). Differently, in the open ocean the lowest occurrence of *M. velascoensis* somewhat precedes the lowest occurrence of *G. pseudomenardii* (Olsson et al., 1999).

### 4.2 Calcareous nannofossils

The calcareous nannofossil assemblages allow to locate the Shaubak, Qreiya and Aweina sections within calcareous nannofossil Zones NP4 – NP5 (Martini, 1971). Zone NP4 is defined by the FAD of *Ellipsolithus macellus* (base) and by the FAD of *Fasciculithus tympaniformis* (top). We consider the first occurrence of *Fasciculithus* an important biostratigraphic event, occurring in the upper part of Zone NP4, following Berggren et al. (1995).

The “Neo-duwi event” bed occurs consistently between the lowest occurrence (LO) of *Fasciculithus* spp. and the LO of *F. tympaniformis*, indicating a very precise stratigraphic position of this event in the uppermost part of Zone NP4, which, following the stratigraphic
schemes of Berggren et al. (1995), would correspond to lowermost planktic foraminifera Subzone P3b.

5 Danian and Selandian Stages

In the type region, Denmark, the Danian- Selandian boundary is marked by an unconformity, between the limestones of Danskekalk Formation and the greensands and marls of the Lellinge Formation (Thomsen and Heilmann-Clausen, 1985) (Fig.3). The time span included in this hiatus is poorly constrained (Thomsen, 1994), because the standard nannoplankton markers of low and middle latitudes for delineating NP4 and NP5 (respectively E. macellus and F. tympaniformis) are missing (Thomsen and Heilmann-Clausen, 1985). Based on data from Gemmas Allé (Denmark), Stouge et al. (2000) assigned the uppermost Danian to the Chiasmolithus bidens Subzone D10 sensu Perch-Nielsen (1979), comparable to part of Zone NP4 (Martini, 1971). The Selandian was assigned to the Toweius selandianus Subzone S2 sensu Perch-Nielsen (1979), equivalent to Zones NP4/NP5 (Martini, 1971) and which include the presence of Neochiastozygus perfectus.

<table>
<thead>
<tr>
<th>Denmark</th>
<th>Zumaya</th>
<th>Middle East</th>
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<td><strong>Stage</strong></td>
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<td><strong>Formation</strong></td>
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<td><strong>Chiasmolithus bidens</strong> Subzone D10</td>
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<td><strong>P3</strong></td>
<td><strong>P2-P3a</strong></td>
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<td><strong>Regional unconformity</strong></td>
<td><strong>Regional unconformity</strong></td>
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</tr>
<tr>
<td><strong>NP4</strong></td>
<td><strong>NP4</strong></td>
<td><strong>Morozovella angulata</strong></td>
</tr>
</tbody>
</table>

Fig. 3 Lithostratigraphy and biostratigraphy of the Danian-Selandian transition in the type region (Denmark), in Zumaya and in the Middle East (Egypt and Jordan).
Moreover, Stouge et al., (2000) assume that based on planktic foraminifera the Danian/Selandian hiatus corresponds approximately to Zone P2 (sensu Berggren et al., 1995).

The Danian and Selandian Stages are chronostratigraphically equivalent to the lower Paleocene and the lower upper (“middle”) Paleocene, respectively. The boundary between these stages is delineated in different ways, using various criteria. Berggren (1994) and Berggren et al. (1995; 2000) proposed to correlate the Danian- Selandian boundary with the P2/P3 zonal boundary, with an estimated age of 60.9 Ma, whereas Hardenbol et al. (1998) estimated the age for sequence boundary Sel 1 in Western Europe at 60.7 Ma (within lower Subzone P3a). Schmitz et al. (1998) studied the Zumaya section in northern Spain and suggest to define the base of the Selandian in a transitional interval including the LO of F. tympaniformis. With current biostratigraphic resolution, this is indistinguishable from the level of the “Neo-duwi event”.

Awaiting formal decision of the stratigraphic position of the Danian/Selandian boundary we refer to the “Neo-duwi event” as a Danian-Selandian transition event, located within Zone P3 and near the top of Zone NP4 between the respective LOs of Fasciculithus spp. and F. tympaniformis. These two events have estimated ages of 59.9 Ma and 59.7 Ma, respectively (based of Berggren et al., 1995); therefore we consider the “Neo-duwi event” to have occurred at ~59.8 Ma. This deviates from the earlier age estimate of 60.5 Ma (Speijer, 2003), which was based on positioning the event within the upper part of Subzone P3a. This now appears unwarranted because of the problematic identification of the P3a/P3b subzonal boundary as outlined above.

6 Results

6.1 Benthic foraminiferal assemblages

In Fig. 4 the stratigraphic and geographic distribution of the main benthic foraminiferal assemblages are represented, characterizing different bathymetric regimes. The Neoeponides duwi assemblage (30~70 m paleodepth) was originally described from southern Egypt (Hewaidy, 1994; Schnack, 2000), an area not included here. Gebel Duwi is characterized by the Anomalinoides umboniferus assemblage, a Midway type assemblage without the deeper dwelling taxa, suggesting middle neritic to shallow outer neritic paleodepth (~70 to 150 m water depth) (Berggren and Aubert, 1975). The Aweina, Nezzi, Qreiya, and Qurtayssiat sections are characterized by the Angulogavelinella avnimelechi assemblage, indicating deep outer neritic to upper bathyal environments (~150-250 m; Speijer and Schmitz, 1998). For more detailed information on these assemblages refer to Speijer (2003). In Shaubak, the Gavelinella beccariiformis assemblage is encountered. Besides the common nominative deep-water taxon, this assemblage is composed of other Velasco type taxa such as Nuttallides truempyi and Angulogavelinella avnimelechi and common Midway type taxa such as Osanguardaria plummerae, Oridorsalis plummerae, Cibicidoides (C. pseudoacutus, C. rigidus),
Anomalinoides praeacutus, Pulsiphonina prima, Alabamina wilcoxensis and various infrequent species. This mixed Midway/Velasco type assemblage is typical of upper bathyal deposits in Sinai (Speijer, 1994; Speijer, 2003). In Shaubak, where the proportion of Velasco type taxa is smaller than in Sinai localities (Speijer, 2003), depositional depth is estimated at 250-300 m. In all sections studied, except Qurtayssiat, the “Neo-duwi event” bed with the N. duwi assemblage interrupts the general assemblage distribution. Neoeponides duwi composes up to 60% the association. Co-occurring components vary somewhat from place to place, but the most common ones are trochamminids, Haplophragmoides, Gaudryna pyramidata, Lenticulina spp., Bulimina strobila, Siphogenerinoides elegantus, Anomalinoides praeacutus, A. umboniferus, Cibicidoides pseudoacutus, Gyroidinoides girardanus, and A. avimelechi. The transitions from the background assemblages to the N. duwi assemblage appear abrupt, not gradual. The same holds true for the transition back to normal background assemblages. It should be noted, however, that the resolution in most sections is too low to be certain on these aspects.

![Fig. 4 Schematic temporal distribution of main benthic assemblages in Danian and Selandian deposits in Egypt (modified after Speijer, 2003) and Jordan. PF – planktic foraminifera Zones (Berggren et al., 1995); CNP – calcareous nannoplankton Zones (Martini, 1971); Ms – Maastrichtian; Th – Thanetian. On the right side, sea-level curve proposed for this interval and compared with Haq et al., (1988) and Hardenbol et al. (1998). Grey band on the right part indicates oxygen deficiency.](image)

### 6.2 Planktic assemblages

#### 6.2.1 Planktic foraminifera: background distributions

Within planktic foraminifera Zone P2, in all sections the assemblages are characterized by the abundance of spinose (Parasubbotina and Subbotina) and praemuricate (Praemurica) taxa, composing together generally more than 95% of the assemblage (Fig. 5). In Shaubak, Subbotina and Parasubbotina are equally well represented (~30%), whereas in the Egyptian localities Parasubbotina is the most abundant spinose taxon (generally ~40%, a maximum of 60% in Duwi). Praemurica constitutes ~30% in all localities, somewhat higher in Duwi (~40% with a peak of ~60%). At Qurtayssiat a hiatus occurs between Zone P1c and P3a, thus no Zone P2 is recorded. In Shaubak, at the transition from Zone P2 to P3, an abrupt
decrease of *Praemurica* (13%) and increase of *Subbotina* (50%) coincides with a thin channel-fill deposit, suggesting differential sorting processes affecting the proportions of the foraminifera.

At the transition between Zone P2 and P3, the muricate genera (*Morozovella, Acarinina* and *Igorina*) appeared, gradually replacing *Praemurica*. In all studied localities, *Praemurica* gradually disappeared within Zone P3a, whereas *Morozovella* rapidly increased. In Qreiya and Nezzi *Morozovella* ranges from <20% (lower Zone P3a) to >60% in middle Subzone P3b, where also *Igorina* starts to increase at the expense of *Parasubbotina*. In Aweina, *Morozovella* is very abundant (>60%) below the “Neo-duwi event”, where the spinose taxa constitute together only <20%. In Shaubak and Qurtayssiat a similar general trend is recorded, but in Zone P3b *Morozovella* is generally less abundant (around 40%), compared to the Egyptian localities. In each locality, the deeper-dwellers *Globanomalina* and *Chiloguembelina* are infrequent (<6%) to rare (<1%), respectively.

Generally, high P/B ratios (70-99%) are encountered in Egypt and Jordan, not indicating any major trends along the record. In Aweina and Nezzi, the P/B ratio is around 80% below the “Neo-duwi event”, and >90% above it. In Duwi and Qurtayssiat, the P/B ratio fluctuates between 80-90%, and in Shaubak and Qreiya slightly higher between 85-95%.

In Shaubak and Duwi, planktic foraminiferal numbers record similar wide variations, (respectively between 160-9,000/g and 400-7,500/g); a slight upwards increase is observed in planktic foraminifera Zone P3b. In Aweina, the numbers mirror the development of the P/B ratio, varying between 120/g and 1,700/g below the event, and up to 4,000/g and more constant above the event.

### 6.2.2 Planktic foraminifera at the “Neo-duwi event”

At the “Neo-duwi event” bed, anomalous planktic foraminiferal assemblages occur in each locality, showing two different patterns, one pattern for the Nile Valley sections (Nezzi, Qreiya and Aweina) and another one for the eastern part of the basin (Duwi and Shaubak). In the Nile Valley, where P/B ratios are very high (>99%) and the carbonate content is slightly enhanced, the fauna is characterized by the abrupt decrease of *Morozovella* (<5%). The association largely consists of poorly preserved, often pyritic or limonitic molds of non-keeled muricate taxa, belonging to low trochospiral *Acarinina* (Plate 1). *Parasubbotina* is also abundant (>30%). During the middle Paleocene, *Acarinina* always occurs in low numbers, but during this event it increases up to >40%. *Globanomalina* and *Subbotina* are also present and record peak values in some cases (8% and 20%, respectively in Aweina).

In Duwi and Shaubak, the pattern is very different, because *Morozovella* remains the most abundant genus. However, large *M. angulata* and *M. conicotruncata* diminish strongly and only small specimens of these taxa are abundant. In Duwi, the number of *Morozovella* slightly decreases (36%) at the “Neo-duwi event”, whereas *Parasubbotina* and *Igorina* increase (23% and 19%, respectively). *Acarinina* only occurs in low numbers (5%).
Fig. 5 All the studied localities are arranged along a transect from the deeper localities on the left to the shallowest on the right. UB – upper bathyal; ON – outer neritic; MN – middle neritic. The relative frequency of planktic foraminifera assemblages is plotted against the planktic/benthic ratio (P/B%), the number of planktic foraminifera/gram (PFN) expressed as logarithmic scale and the carbonate content (CaCO3%). The grey bands indicate intervals of dissolution. The horizontal bar indicates the “Neo-Duwi event”.
In Shaubak, small *Morozovella* dominates the assemblage, reaching a maximum value (55%), and *Acarinina* increases (14%).

At Duwi and Aweina, rare specimens of *Praemurica* reappear at the base of the “Neo-duwi event”, indicating reworking.

In spite of similar P/B ratios in all sections, some differences across the “Neo-duwi event” can be distinguished between individual localities. In the Nile Valley, P/B ratios below and above the event drop to values <20% and coincide with very low carbonate content and poorly preserved foraminifera, suggesting significant post-depositional dissolution. The highest P/B ratios (>99%) are observed at the base of the event, coinciding with the dominance of *Neoeponides duwi* amongst the benthic foraminifera and a slight increase of the carbonate content. In contrast, in Shaubak and Duwi the P/B ratios just slightly decrease below the event bed (to 83% and 70% respectively) and there is no major change within the event bed.

In Aweina, planktic foraminiferal numbers fluctuate within “Neo-duwi event” bed between 500/g to 11,000/g; whereas in Shaubak and Duwi the planktic foraminiferal numbers slightly decrease just below the “Neo-duwi event” (respectively 277/g and 388/g), but increase again within the bed.

6.2.3 Calcareous nannofossils

The studied assemblages (Shaubak, Aweina, Qreiya), are generally characterized by common *Coccolithus pelagicus*, *Ericsonia*, *Neochiastozygus* (including *N. perfectus*), *Prinsius*, *Thoracosphaera*. Few to common *Chiasmolithus*, *Cruciplacolithus* (including *C. tenuis*), *Ellipsolithus* (including *E. macellus*) *Fasciculithus* (including *F. tympaniformis*), *Touveius*, *Placozygus sigmoides* and a number of rare taxa.

In Shaubak, at the base of the “Neo-duwi event”, an anomalous fauna, dominated by small *Prinsius martini*, interrupts this assemblage. *Coccolithus pelagicus*, *Cruciplacolithus* and *Thoracosphaera* are few, together with rare specimens of *Ericsonia* and *Neochiastozygus*. All other taxa disappear temporarily.

In Aweina, across the “Neo-duwi event” (between samples -18-25 cm to +4-9 cm), samples are nearly barren and the preservation is poor, indicating dissolution. Different from Shaubak, *Ericsonia* is abundant. *Coccolithus pelagicus*, *Cruciplacolithus* are few; *Chiasmolithus*, *Ellipsolithus* and *N. perfectus* are rare. All other taxa are absent. In Qreiya the situation is similar to Aweina, with a nearly barren interval spanning the “Neo-duwi event” (between samples 271185/42 and 271185/39).
6.3 Carbonate content

In the Nile Valley (Aweina, Nezzi, Qreiya), the marls contain between 15 and 60% CaCO₃ (Speijer and Schmitz, 1998; Speijer, 2003). Similarly, in the Jordanian sections the marls generally contain between 20 and 60% CaCO₃. In Shaubak, only the channel fill yields an anomalously high peak of 84%. This probably relates to the sandy texture, caused by the high concentration of foraminifera.

In the Nile Valley, the "Neo-duwi event" bed contains about 20% CaCO₃ and it is sandwiched between shaley beds (20-50 cm thick) containing <10% CaCO₃, coinciding with low P/B ratios. In contrast, in Shaubak no significant changes are observed across the event bed. The low carbonate content might be explained by increased terrigenous input related to increased continental erosion and dilution of carbonates into the basin. Post-depositional dissolution must have also further influenced the low carbonate interval below and above the "Neo-duwi event".

6.4 Stable isotopes

6.4.1 General trends

Calcareous nannofossils and planktic foraminifera are the main carbonate component, so the whole-rock isotopic records are primarily constituted by upper water column signals.

In the studied successions, whole-rock δ¹³C values mostly vary between -1‰ to 0‰ (Fig. 6, Appendix). The outer neritic Nezzi and Aweina sections record the most negative values of ~-1‰ in Zone P2 and Subzone P3a (~-1.2‰ recorded ~1.5m below the “Neo-duwi event” in Aweina), and increase up to about -0.6‰ in Subzone P3b. In the deeper Qreiya and Shaubak sections, the values are slightly (0.3‰) higher than in Aweina and about 0.8‰ lower than Ben Gurion (Charisi and Schmitz, 1998). Ben Gurion is the deepest locality (~500 m paleodepth), and exhibits the heaviest δ¹³C values compared to shallower localities, suggesting less influence from terrestrial runoff. In fact, the pattern of the δ¹³C confirms the bathymetric arrangement of the localities.

In each locality, the δ¹⁸O values show a wide range, from ~-6‰ to ~-3‰. The lowest values are recorded in planktic foraminifera Zone P2 in single samples in Shaubak and Qreiya (respectively ~-5.3‰ and ~-4.8‰).

A general pattern can also be recognized in the δ¹⁸O records: Ben Gurion shows the highest values (between -2.8‰ and -2‰). Lower values are recorded in Aweina and Qreiya (between ~-3‰ and -4‰) and even lower in Nezzi and Shaubak (between ~-4‰ and -5‰). This suggests that the coolest waters are encountered at Ben Gurion.

Overall, a small upwards increase towards less negative values is recorded in the δ¹⁸O records of Ben Gurion, Shaubak and Qreiya.

An indication of a strong diagenetic overprint is provided by the sandy channel deposit (uppermost Zone P2) in Shaubak, where the lowest values δ¹³C (~-3.18‰) and δ¹⁸O (~-5.16‰) are recorded.
Fig. 6 Carbonate and oxygen stable isotopes on whole-rocks are represented, plotted against biostratigraphy. Data on Ben Gurion are from Charisi and Schmitz (1998), B-bathyal. The bar indicates the “Neo-dwali event”. On the right bottom corner, close-up of the “Neo-dwali event” at Aweina.
6.4.2 Stable isotope fluctuations at the “Neo-duwi event”

In Shaubak, a positive $\delta^{13}C$ shift of $\sim 0.5\permil$ is recorded at the base of the “Neo-duwi event” bed. In Aweina, the carbonate isotope record generally increases across the “Neo-duwi event”, through various steps reaching a peak of $\sim 0\permil$ at 24.9 m. This increase is interrupted by short negative wiggles, one of $\sim 0.5\permil$, corresponding to the base of the “Neo-duwi event”. In Qreiya at the “Neo-duwi event”, a first small $0.2\permil$ negative shift is recorded at the base, followed by a second shift of $\sim 0.3\permil$ at 0.2 m above it. This pattern could not be identified in Gebel Nezzi, because of the low-resolution of this dataset.

Similar fluctuations are recorded also in the $\delta^{18}O$. In Shaubak the $\delta^{18}O$ increases of $\sim 1\permil$ toward heavier values (-3.2‰). Instead, in the Nile Valley the generally constant pattern is interrupted by a negative shift of $\sim 1\permil$ in Qreiya and Nezzi (-4.3‰ and -5.2‰, respectively). In Aweina, a negative variation of $\sim 2\permil$ occurs through various steps. These records suggest a strong diagenetic overprinting of the values at the “Neo-duwi event”.

7 Discussion

7.1 Calcareous planktic assemblages

7.1.1 Evolutionary trends and paleoecology of Paleocene planktic foraminifera

The Danian-Selandian transition (61-59 Ma) was a time of significant diversification of planktic foraminifera. In particular, the creation of different specialized depth habitats played an important role in the diversification of planktic foraminifera, related to the initiation of photosymbiosis as a trophic strategy (Quillévéré and Norris, 2003). Subbotinids and globanomaliniids probably preferred living within or below the thermocline, whereas acarininids, morozovellids and igorinids inhabited the surface mixed-layer (Shackleton et al., 1985; Pearson et al., 1993; D’Hondt et al., 1994; Van Eijden, 1995; Kelly et al., 1996a; Lu et al., 1998b; Quillévéré and Norris, 2003). Stable isotopic values indicate that subbotinids grew in cooler, deeper waters than morozovellids and their spinose texture suggests that they may have been carnivorous (Boersma and Premoli Silva, 1991; Norris, 1996), in analogy to modern carnivorous, non-photosymbiotic, *Globigerina bulloides* (Berggren and Norris, 1997). In the modern ocean, *G. bulloides* is a well known sub-polar species, with preference for upwelling conditions (Bé, 1977), in general reflecting conditions of enhanced productivity (e.g. Ganssen and Kroon, 2000).

Early species of *Acarinina*, prior to 57 Ma were characterized by more positive $\delta^{18}O$ values than *Morozovella* and later *Acarinina* species, indicating a deeper (and cooler) habitat (Berggren and Norris, 1997; Quillévéré et al., 2000; Quillévéré and Norris, 2003). This could explain why acarininids were abundant and widely diversified at high latitudes during the Paleocene, while morozovellids were absent (Quillévéré and Norris, 2003). It is also generally accepted that most morozovellids, acarininids and igorinids were photosymbiotic (D’Hondt
et al., 1994; Norris, 1996; Berggren and Norris, 1997; Quillévéré and Norris, 2003). Consequently, the acquisition of photosymbionts may have facilitated the radiation of acarininids and morozovellids during late Paleocene expansion of oligotrophic conditions in the global ocean, allowing these taxa to thrive in low-nutrient water masses (Kelly et al., 1996b; Norris, 1996; Quillévéré and Norris, 2003). Similar as in the modern ocean, the photosymbiotic species are thought to have had a greater ability to withstand periods of nutrient stress (Norris, 1996). Kelly et al. (1996a) suggested that the acquisition of photosymbiosis occurred at the transition from *Praemurica inconstans* to *Morozovella angulata* (Zones P2-P3a). On the other hand, it remains somewhat contradictory that the capacity to thrive in oligotrophic conditions through the acquisition of symbionts occurred exactly at a time in which geochemical data, such as the increase $\delta^{13}$C and barite deposition, suggest enhanced surface productivity (Shackleton et al., 1985; Corfield and Cartlidge, 1992; Thompson and Schmitz, 1997; Charisi and Schmitz, 1998).

<table>
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<tr>
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<td>photosymbiotic, warm, oligotrophic water</td>
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<td>ML</td>
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<td>photosymbiotic, oligotrophic water</td>
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<td>Acarinina</td>
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<td>2,4,6,7,11,13</td>
<td>photosymbiotic, oligotrophic water</td>
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<tr>
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<td>Low T</td>
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<td>cold mesotrophic water</td>
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<td>Praemurica</td>
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<td>Chiloguembelina</td>
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The general evolutionary trend from assemblages dominated by spinose and praemuricate taxa towards assemblages dominated by muricate taxa is observed in the study area. In planktic foraminifera Zone P2 spinose genera (*Subbotina* and *Parasubbotina*) and *Praemurica* (in less numbers) dominated the water column. In addition, in the shallowest locality (Duwi) *Praemurica* exhibited the highest abundances, suggesting a preference of this taxon for shallower (and perhaps warmer) water. Already in upper Zone P2, the earliest specimens of *Morozovella* and *Acarinina* are observed, belonging to *M. praeangulata* and *A. praeaequa*, respectively. Our data show that *Praemurica* survived up into Subzone P3a in the southern Tethys, where gradually, the muricate taxa *Morozovella*, *Acarinina* and *Igorina* successfully replaced *Praemurica*. This is in contrast with the observations of Olsson et al., (1999) on oceanic records, where *Praemurica* last occurred at the top of Zone P2 or base of Zone P3.
7.1.2 Response of the calcareous plankton to the "Neo-duwi event"

At the "Neo-duwi event", the planktic assemblages show a transient anomaly, but in contrast to the simultaneous benthic perturbation with one species dominating in all localities, the pelagic excursion shows differential patterns within the basin. In fact, since the same anomalous bottom-water benthic assemblage characterizes similar deposits, this would suggest similar surface water conditions. In particular, considering the vicinity of these localities one would expect the same oceanic regime. However, apparently in contradiction, the planktic foraminiferal assemblages are dominated by different taxa, suggesting that different processes were settled.

In the Nile Valley (Nezzi, Aweina, Qreiya) the incursion of *N. duwi* corresponds to an increase of *Acarinina* and *Parasubbotina*, indicating that very different conditions affected the upper water column. Considering that early acarininids were probably occupying a deeper, cooler and mesotrophic habitat (Quillévéré and Norris, 2003), the conditions established at the "Neo-duwi event", seem to have favored the lower mixed layer and the thermocline dwellers. Particularly the surface dweller *Morozovella* was suppressed during this interval. It could be argued that differential dissolution may have reduced the relative numbers of *Morozovella* (e.g. Boersma and Premoli Silva, 1983), but the high P/B ratios (>80%) and the planktic foraminiferal numbers (500-11,000 in Aweina) indicate that this effect can be neglected. Therefore, the abrupt increase of *Acarinina* must represent a primary signal. We suggest that *Acarinina* may have had a higher tolerance for lower salinity than *Morozovella* and that enhanced run-off during the "Neo-duwi event" lead to the collapse of the symbiotic relationship of *Morozovella*. At the same time also *Parasubbotina* flourished. Since, *Parasubbotina* shared a similar isotopic composition and wall-texture with *Subbotina* it is plausible that these taxa shared a similar trophic strategy and living position within the thermocline. Increased productivity through enhanced input of nutrients from land may have favored the thermocline dwellers *Parasubbotina*.

We observe a different situation at Shaubak and Duwi, where small-sized morozovellids dominated the planktic foraminiferal assemblages, indicating that very different conditions affected the upper water column. During the Holocene upwelling areas are characterized by small-sized specimens of planktic foraminifera (Hallock, 1987; Schmidt et al., 2004) and high abundance of a few species, with an opportunistic behavior and simple morphology (Boersma and Premoli Silva, 1991). Through analogy, we infer that the increase of small specimens of *Morozovella* may have represented a signal of enhanced productivity trough upwelling. This would be in agreement with the bloom of small *Prinsius martinii* which is indicative of cooler water and high nutrient supply as in upwelling situations (Orue-Extebarria et al., 1996; Bolle et al., 1999; Tremolada and Bralower, 2004). Although an increase of symbiont-bearing *Morozovella* during enhanced productivity seems contradictory, this phenomenon is also known from recent species. For instance, *Globigerinoides ruber* is a surface dwelling spinose symbiont-bearing species (Pujol and Vergnaud-Grazzini, 1995), and its increased abundance can be associated to enhanced
primary productivity in the central part of the eddy in the Caribbean Basin (Schmuker and Schiebel, 2002). In fact, absence of symbionts bearing in upwelling areas is connected to high turbulence and not to nutrient availability. Clearly, our ecological inferences are speculative, but they underscore that the ecology of Paleocene planktic foraminifera is still poorly understood and that, just as for modern taxa, the relationships between distributions and biotic and physicochemical parameters were probably much more complex than currently envisaged.

7.2 Paleoceanographic scenario

Prior to the “Neo-duwi event”, diversified benthic and planktic foraminiferal, and nannofossil assemblages indicate a well-oxygenated and relatively oligotrophic basin, both in the water column and on the seafloor. Under these conditions, various benthic foraminiferal assemblages are arranged along a paleobathymetric gradient (Speijer, 2003). The abundance of Morozovella, Subbotina and Parasubbotina and the scarcity of Chiloguembelina suggest a well-stratified and oxygenated water column, particularly from Zone P3 upwards, in which a mixed layer and thermocline can be identified. In addition, the high abundance of Morozovella and low numbers of Igorina and Acarinina point to warm surface waters, which fits well with a paleolatitude of 10-15° N (Barron et al., 1981).

This general stability was interrupted by a transient period of environmental stress, reflected in anomalous surface-water and seafloor assemblages at the “Neo-duwi event”. It was suggested earlier (Speijer, 2003) that the “Neo-duwi event” involved a sea-level cycle with a sea-level low just prior to the event possibly correlative with sequence boundary Sel 1 of Hardenbol et al. (1998). During early sea-level rise, enrichment in TOC, pyrite, fish remains and anomalously high P/B ratios indicate oxygen-poor seafloor conditions. The present data indicate that oxygen deficiency was associated with enhanced productivity. In addition, our observations point towards two different paleoenvironmental settings within the basin.

In the eastern part of the studied area (Shaubak and Gebel Duwi) an upwelling system settled. Upwelling of nutrients into the mixed layer enhanced primary productivity and, consequently, favored surface dwelling foraminifera thriving on this.

In contrast, in the Nile Valley the rarity of Morozovella and the dominance of Acarinina suggest stronger water column stratification due to pronounced freshwater influence on the surface. In this situation, nutrient-rich freshwater led to higher primary productivity and stratification of the water column.

In southern Egypt, a northward prograding deltaic system has been described associated with a long-term regressive phase during the middle Paleocene (Hendriks et al., 1985; Luger, 1988; Luger et al., 1990). This is confirmed also in the paleogeographic reconstruction proposed by Guiraud and Bosworth (1999). They described fluvial deposition located in South Egypt during the late Paleocene (fig. 7). The duration of this regressive phase was much longer than the duration of the “Neo-duwi event”, but it is plausible that a pulse of
enhanced river discharge in the Nile Valley during the “Neo-duwi event” contributed significantly to this progradation. On the other hand, the event bed is thought to have been deposited during rapid sea-level rise and thus we suggest increased precipitation and runoff resulted from climatic change.

In the present world, regions in which river plume is superimposed to upwelling system are characterized by a complexity of variability, as results of interaction of currents and winds systems, river discharge and seasonal variation. Therefore, different oceanic regimes can cause different sediment assemblages of microfossils within few kilometer distances. In areas of high river discharge, sharp oceanic fronts, due to temperature and salinity changes, are often present. In these areas, faunas may change within several hundred meters (Ralf Schiebel, pers. comm.).

For instance, in the eastern South Atlantic closed to the Congo River plume different planktic foraminiferal assemblages are correlated to different surface-water masses.

For instance, warm saline plume in front of the Congo River is dominated by *Globigerinoides ruber* pink-*Neogloboquadrina dutertrei* assemblage, whereas the coastal upwelling areas are dominated by *N. pachyderma-Globigerina bulloides* (Ufkes et al., 1998). The distribution of planktic foraminifera correlates to physico-chemical properties of the water masses and different nutrients available. Whereas, studies on benthic foraminifera in the same area (Leg 175, Site 1079 and GeoB1016) indicate a dominance of low oxygen-tolerant taxa during period of increased productivity, such as bolivinids, buliminids, *Epistominella* and *Uvigerina* (Pérez et al., 2001). Within this assemblage, *Bolivina pseudopunctata* and *Bolivina dilatata* seem to prefer marine organic carbon or terrigenous organic matter, respectively.

**Fig. 7** Paleogeographic map of Egypt during the upper Paleocene (modified after Guiraud and Bosworth, 1999).
Low oxygen-tolerant benthic assemblage dominated also at the “Neo-Duwi event”, although the bottom-floor conditions during this event seem to be extreme.

As sea level continued to rise and the climatic and oceanographic conditions normalized, river discharge (in the Nile Valley) and upwelling (in the eastern part) ceased and sea-floor oxygenation improved. Consequently, the normal relatively stable benthic and planktic foraminiferal and nannofossil assemblages reappeared.

The isotopic data across the “Neo-duwi event” are strongly affected by diagenesis, due to recrystallization of carbonate in the presence of meteoric water (depleted in $^{18}$O), which may carry $^{12}$C derived from the degradation of organic matter strongly altered the primary isotopic signals (Corfield et al., 1991). Therefore, the stable isotopic records across the “Neo-duwi event” do not support or rule out any interpretation.

### 7.3 A Danian-Selandian hyperthermal?

Several features of the “Neo-duwi event” strongly remind us of those associated with the PETM as it is developed in Egypt and Jordan (Speijer and Wagner, 2002; Chapter V). These similarities point to analogous operative processes. Some of these aspects were previously discussed (Speijer, 2003).

During the PETM, *Acarinina* dominated the planktic assemblages in the Tethyan area (Arenillas and Molina, 1997; Lu et al., 1998a; Arenillas et al., 1999; Molina et al., 1999; Pardo et al., 1999) and in the ocean (Kelly et al., 1996b; Kelly et al., 1998; Kelly, 2002). Various authors (Kelly et al., 1996b; Arenillas and Molina, 1997; Kelly et al., 1998; Kelly, 2002) agree on explaining this increase as a response to oligotrophic conditions, under which symbionts would have helped *Acarinina* to survive. Why symbiont-bearing and surface-dwelling *Morozovella* was not able to do the same and almost completely vanished remains, however, unexplained in this way. Instead most other proxies, such as benthic foraminifera (Speijer et al., 1996; Speijer and Schmitz, 1998; Thomas et al., 2000), calcareous nannofossils (Monechi et al., 2000), siliceous plankton and organic dinocysts (Crouch et al., 2001; Egger et al., 2003), geochemistry (Bains et al., 2000; Speijer and Wagner, 2002) point to eutrophic conditions in various continental margin basins. Enhanced productivity has been related to either intensified upwelling (i.e. Bolle et al., 2000; Speijer and Wagner, 2002) or a combination of increased weathering and run off (Crouch et al., 2003; Gavrilo et al., 2003). In Egypt, the PETM is characterized by the invasion of opportunistic middle neritic *Anomalinoïdes aegyptiacus* assemblage in response to eutrophic conditions and poor and variable seafloor oxygenation (Speijer and Wagner, 2002).

During the “Neo-duwi event”, we also observe the flourishing of *Acarinina* in the Nile Valley sections, as pointed out in response to increased runoff and productivity and lowered salinity. In addition, the *Neoeponides duwi* assemblage seems to represent a similar opportunistic strategy towards dysoxic to anoxic conditions as the *Anomalinoïdes aegyptiacus* assemblage during the PETM. Both events are also characterized by a rapid sea-level rise after a sea level low-stand (Speijer, 2003).
The stable isotopes at the “Neo-duwi event” are strongly hampered by diagenesis, thus not comparable to the excursion at the PETM.

In the deep ocean, various hyperthermals have been suggested before and after the PETM (Thomas and Zachos, 2000; Thomas et al., 2000; Bralower et al., 2002), but are still awaiting confirmation by more detailed and extensive studies. Some of the suggested hyperthermals (i.e. in planktic foraminifera Zones P3a and P4) are associated with anomalous foraminiferal assemblages (Thomas and Zachos, 2000; Bralower et al., 2002). At present, there is no evidence of a hyperthermal at 59.8 Ma recorded in the open ocean. On the other hand, our studies provided unexpected difficulties in the application of standard zonation schemes for the middle Paleocene that it cannot be excluded that mismatches between climatic events in continental margin and oceanic records may have resulted from poor age calibrations. We believe that some key bio-events (nannofossils and foraminifera) were probably not synchronous in the Tethys and in the ocean and that, the age model of bio-events needs further refinement. Although we cannot rule out that the “Neo-duwi event” represents only a local paleoenvironmental phenomenon, we speculate that it could have resulted from a significant climatic event at the beginning of the long-term warming trend of the early Paleogene.

Conclusions

The Danian-Selandian transition in Egypt and Jordan is marked by a transient biotic change during the “Neo-duwi event”. Our results demonstrate sedimentological, faunal and geochemical variations, which point toward variations in productivity related to paleoclimatic and paleoceanographic changes:

1. The “Neo-duwi event” is distinguished by the deposition of a dark organic-rich bed, with abundant fish remains and planktic foraminifera.
2. Benthic foraminiferal assemblages are dominated by a bloom of the shallow water Neoeponides duwi, temporarily replacing the normal bathymetrically arranged assemblages.
3. Planktic foraminiferal assemblages show two main patterns within the basin. In the Nile Valley, an increase of Acarinina and Parasubbotina suggest lowered salinity and increased nutrient supply trough enhanced river discharge. In the eastern part of the basin (Duwi and Shaubak), flourishing of minute Morozovella and a bloom of small Prinsius martinii suggest increased upwelling.
4. The dominance of Acarinina and Morozovella is in line with a different ecology of these taxa. Early Morozovella was probably less tolerant to lowered salinity and was better able to cope with enhanced nutrient levels.
5. Faunal, sedimentological and geochemical similarities between the “Neo-duwi event” and the PETM in the studied basin suggest similar paleoenvironmental processes,
and suggest that the “Neo-duwi event” may have been the local expression of a significant climatic event.

Acknowledgments

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Plate 1

1. Acarinina sp. Sample Gebel Aweina BB
2. Acarinina sp. Sample Gebel Aweina BB
3. Acarinina sp. Sample Gebel Nezzi 51285/19
4. Acarinina sp. Sample Gebel Nezzi 51285/19
5. Parasubbotina sp. Sample Gebel Qreiya 271185/41
6. Acarinina sp. Sample Gebel Qreiya 271185/41
7. Acarinina sp. Sample Duwi DU40
8. Subbotina sp. Sample Duwi DU40
9. Morozovella sp. Sample Shaubak SHA 90
10. Parasubbotina sp. Gebel Nezzi 51285/19
11. Neoeponides duwi, sample Shaubak SHA 90
12. Neoeponides duwi, sample Shaubak SHA 90

scale bar: 50µm
References


## Appendix

<table>
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<th>Localities</th>
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<th>Foraminifera biozone (Berggren et al., 1995)</th>
<th>Nannofossils biozone (Martini, 1971)</th>
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**Gebel Qreiya**

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CHAPTER V

The Paleocene-Eocene thermal maximum in Egypt and Jordan: an overview of the planktic foraminiferal record

Elisa Guasti and Robert P. Speijer

Submitted to GSA special publication "Large Ecosystem Perturbations: Causes and Consequences"
CHAPTER V

The Paleocene-Eocene thermal maximum in Egypt and Jordan: an overview of the planktic foraminiferal record

Elisa Guasti and Robert P. Speijer

Abstract

In the present study, we investigate planktic foraminiferal assemblages of Zone P5 in Egypt and Jordan across middle neritic to upper bathyal transect of the Tethyan continental margin. In particular, we evaluate the planktic foraminiferal turnover and the diversification of new taxa across the Paleocene-Eocene thermal maximum (PETM). Dissolution affects the planktic assemblages more intensively than previously considered, especially in the marls below the PETM. High numbers of *Subbotina*, fluctuating P/B ratios and low numbers of planktic foraminifera/g are indicative of dissolution, probably as a consequence of deep weathering. Hence, high numbers of *Subbotina* in this area do not indicate cooling. Despite this taphonomic overprint, we observe that well diversified planktic foraminiferal assemblages of Subzone P5a abruptly change into oligotaxic assemblages dominated by *Acarinina* during the PETM. Because various biotic and geochemical proxies indicate increased nutrient supply to the basin, we argue that the blooming of *Acarinina* is not indicative of oligotrophic conditions. Instead, we speculate that (low-trochospiral) *Acarinina* may have been better adapted to thrive under stressed environmental conditions, because they possibly hosted symbionts different from those in *Morozovella*. Finally, it is inappropriate to subdivide Zone P5 on the basis of the occurrence of *Acarinina sibaiyaensis*, because this taxon occurs in Egypt and off Senegal well before the PETM. Instead, we propose *A. multicamerata* sp. nov. as the biozonal marker of Subzone P5b.
1 Introduction

The Paleocene-Eocene thermal maximum (PETM) represents a period of extreme global warmth (Zachos et al., 1993), associated with a major extinction of deep-sea benthic foraminifera (Tjalsma and Lohmann, 1983; Thomas, 1998), and evolutionary rejuvenations among planktic foraminifera (Kelly et al., 1996b), mammals (Clyde and Gingerich, 1998), calcareous nannofossils (Aubry, 1998), diatoms (Oreshkina and Oberhänsli, 2003) and ostracodes (Speijer and Morsi, 2002). Associated to this interval is a negative 2-3‰ carbonate isotopic excursion (CIE) (Kennett and Stott, 1991; Koch et al., 1995). For a period of about “60,000” years, “superwarm” conditions developed at what is known as the Paleocene-Eocene thermal maximum. What triggered the event is still under debate. The most widely accepted idea is that initial deep-sea warming led to the massive dissociation of oceanic methane hydrates, leading to further warming (Dickens et al., 1995). Other theories involve an increase of volcanic emission (Eldholm and Thomas, 1993) or a comet impact (Kent et al., 2003). A new alternative proposes intrusion of mantle-derived melts carbon-rich sediments in the northeast Atlantic as cause for an explosive release of methane (Svenses et al., 2004).

It is also heavily debated whether this “supergreenhouse” period was associated with increased or decreased oceanic productivity. Several oceanic records and particularly the calcareous nannofossils suggest widespread oligotrophy (Kelly et al., 1996b; Bralower, 2002). In contrast, most continental margin records suggest an increase in productivity (Speijer et al., 1996a, 1996b, 1997; Schmitz et al., 1997; Crouch et al., 2001; Speijer and Wagner, 2002; Gavrilo et al., 2003) and also some open ocean records provide evidence for this (e.g. Thompson and Schmitz, 1997; Bains et al., 2000; Thomas et al., 2000; Stoll and Bains, 2003). An overall increase in oceanic productivity and burial of organic carbon in marine sediments would provide an important negative feedback mechanism (Bains et al., 2000; Dickens, 2001; Speijer and Wagner, 2002). Bains et al. (2000) suggest that an increase of nutrient supply can cause blooms in marine phytoplankton, which may sequester the greenhouse gas CO₂ to the deep sea by about 60,000 years of enhanced biological “pumping”. This bloom might be a response to a combination of increased weathering and runoff from the continents, oceanic fertilization from volcanic fallout, rising temperatures and increase atmospheric CO₂ concentrations (Bains et al., 2000 and references therein).

The southern Tethyan margin appears 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 boundary stratotype section and point (GSSP) for the Paleocene/Eocene boundary has recently been defined in Egypt within the Dababiyah Quarry section, near Luxor in the Nile Valley (Ouda and Aubry, 2003).

The PETM in Egypt has been intensively investigated mainly on the basis of benthic foraminifera (Speijer, 1994; Speijer et al., 1996a, 1996b, 1997, 2000; Youseff, 2003),
planktic foraminifera (Obaidalla, 2000; Berggren and Ouda, 2003; Ouda et al., 2003), nannoplankton (Aubry et al., 1996; Monechi et al., 2000, Tantawi et al., 2003; Youseff, 2003), ostracodes (Speijer and Morsi, 2002), and geochemical and mineralogical parameters (Charisi and Schmitz, 1995, 1998; Schmitz et al., 1996, 1997b; Bolle et al., 2000b; Speijer and Wagner, 2002; Dupuis et al., 2003; Knox et al., 2003).

In this study, we evaluate the planktic foraminifera assemblages, along an inner neritic to upper bathyal transect, from exposures in Egypt (Nile Valley, Eastern Desert and Sinai) and in Jordan (Fig. 1). They are situated in an extensive epicontinental basin that covered most of Egypt, Israel and Jordan at the end of the Paleocene (Speijer and Wagner, 2002), deepening in a northwest direction. The area is characterized by two major tectonic provinces, the stable shelf in the south (also known as Nile Basin) and the unstable shelf in the north (Syrian Arc) (Said, 1990; Shahar, 1994). The localities studied in this work belong to the stable shelf (Said, 1990; Youssef, 2003). Benthic foraminiferal data indicate that shallowest deposition occurred at Gebel Duwi (middle neritic, ~50-100 m) and the deepest at Wadi Nukhl (upper bathyal, ~500-600 m) (Speijer et al., 2000). Gebels Aweina, Qreiya, Dababiya and Qurtassyat represent outer neritic localities. Dababiya was slightly shallower (~150-175) than the other localities (~200m).

This transect provides a good opportunity to document the planktic foraminiferal developments across the PETM. Planktic foraminiferal assemblages dominated by *Acarinina* characterize the PETM in open marine environments worldwide. This has been interpreted as an indication of oceanic oligotrophy (Kelly et al., 1996b, 1998). However, we consider it highly unlikely that oligotrophic conditions of the open ocean could also prevail on the Tethyan margin, where, by contrast, all other proxies suggest an increase of nutrients and/or productivity. Therefore, we re-evaluate previous paleoecological interpretations of this typical PETM planktic foraminiferal assemblage. Moreover, we demonstrate that the sub-biozonation of Zone P5 based on the occurrence of *Acarinina sibaiyaensis* leads to
miscorrelations, because this taxon, together with *A. africana*, occurs well before the PETM. This results mainly from taxonomic ambiguities, but these need to be resolved first prior to introducing a formal subzonation of Zone P5. Hence, we introduce *Acarinina multicamerata* as biozonal marker of a new Subzone P5b. *Acarinina multicamerata* and *M. allisonensis* are the only planktic foraminiferal excursion taxa, which are thus far exclusively observed at the PETM.

2. Material and Methods

Samples were collected from 6 locations. Low-resolution sample sets (~1 m) of Gebel Qreiya, Wadi Nukhl and Gebel Qurtayssiat could be used. For Duwi and Aweina centimeter scale sample sets across the PETM were available. Samples of the Dababiya DBH section, a 6-m-thick section comprising the GSSP of the Paleocene/Eocene boundary were provided by Christian Dupuis (Polytechnic of Mons). In order to further enhance the resolution of the Dababiya DBH record, additional samples were collected on the occasion of the inauguration of the GSSP of the P/E boundary during the Climate and Biota of the Early Paleogene conference (CBEP IV) in Luxor, 2004. In the Dababiya and Qreiya sections, the P/E boundary is well defined at the basis of a non-calcareous clay to siltstone (Dupuis et al., 2003; Knox et al., 2003). In the Aweina section, the P/E boundary is situated at an omission surface between the marls of Esna unit 1 and the overlying calcarenitic bed. Abundant bioturbations extend some 7 cm down from the calcarenitic into the underlying marls (Speijer et al., 1996a; Schmitz et al., 1997b).

All samples were processed according to standard microplaeontologic procedures explained in Speijer et al. (1996b) (samples from Egypt) and in Chapter IV (samples from Jordan). The fraction >125µm was used for all foraminiferal studies. Compositional data of the planktic foraminiferal assemblages were determined, counting 200-300 specimens classified at genus level, generally using the concepts of Berggren and Norris (1997) and Olsson et al. (1999). In addition, the percentage planktics in the foraminiferal association (P/B ratio, expressed as 100xP/(P+B), cf. (Van der Zwaan et al., 1990), as well as the total number of planktic foraminifera per gram of dry sediment (PFN) were calculated.

Carbonate content and whole-rock stable isotopes (O, C) were measured for the Qurtassyat section at the Free University of Amsterdam (see table 1). These parameters have been presented for the other sections in earlier studies (Speijer et al., 1996a; Schmitz et al., 1996; Speijer and Wagner, 2002; Dupuis et al., 2003).
Table 1. Carbonate content and carbonate isotopic record from Gebel Qurtaayssiat.

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</table>

3 Planktic foraminiferal excursion taxa

In open ocean ODP sites and in the marginal Tethys, a number of authors describe the occurrence of new planktic foraminifera taxa, called “excursion” taxa, including *Acarinina sibaiyaensis*, *A. africana* and *Morozovella allisonensis*, coinciding with the PETM (Kelly et al., 1996b, 1998; Bolle et al., 2000a; Berggren and Ouda, 2003; Ouda et al., 2003). In addition, the lowest occurrence (LO) of *A. sibaiyaensis* has been proposed as a zonal marker of Subzone P5b by several authors (Molina et al., 1999; Pardo et al., 1999; Berggren and Ouda, 2003). Alternatively, Speijer et al. (2000) suggested the total range of *M. allisonensis* as zonal marker of Subzone P5b.

The holotypes of *Acarinina sibaiyaensis* and *A. africana* were originally described by El-Naggar (1966) as *Globorotalia sibaiyaensis* and *Globorotalia africana*, respectively (Pl. 1). He observed these species in the “upper Paleocene” upper Aweina shale (= Esna Fm.) in Egypt. *Globorotalia sibaiyaensis* El-Naggar was described as a compressed small, globular species, in which the last whorl is composed of 5½ chambers, with a long narrow aperture. El-Naggar (1966) suggested that this taxon may have evolved from *G. perclara* Loeblich and Tappan (1957), which already occurred in the Danian.

Our observations uncover a number of problems on the evolution, morphology and range of *A. sibaiyaensis* in the literature. For instance, Kelly et al. (1998) provide a very different description of *A. sibaiyaensis* compared to the holotype description. These authors consider *A. sibaiyaensis* as a globular flat species with 6 to 9 chambers, which seemed to evolve from *Acarinina soldadoensis*. To support this evolutionary change, Kelly et al. (1998) show a morphological sequence from *A. soldadoensis* to *A. sibaiyaensis* (Fig. 9, p. 150). In our view, the specimen presented as *A. soldadoensis* (specimen “A”) in this cline seems already very close to *A. sibaiyaensis* sensu El-Naggar (1966) and quite different from *A. soldadoensis*. 

117
**Acarinina soldadoensis** Bronniman is composed of 4 (occasionally 5) chambers increasing in size, distinctively elongated in the direction of the axis of the test; at the umbilical side the chambers tend to become pointed. The sutures of the spiral side are oblique, giving the impression of overlapping chambers. These diagnostic features seem to be missing in the specimens considered by Kelly et al. (1998) as *A. soldadoensis*. To the other end of the cline, the multi-chambered (6-9 chambers) forms of *A. sibaiyaensis* sensu Kelly et al. (1998) can easily be distinguished from *A. sibaiyaensis* sensu El Naggar (1966), although they may be linked phylogenetically.

Arenillas et al. (2004) find specimens of multi-chambered *A. sibaiyaensis* at the PETM. These authors suggest that *Acarinina strabocella* could have been the ancestor of *A. sibaiyaensis*, although this would be in conflict with observations by various authors, who record the highest occurrence of *A. strabocella* in lower Zone P4 (Lu et al., 1998b; Olsson et al., 1999).

Apparently, several authors find specimens of what they consider “*A. sibaiyaensis*”, but morphologically quite different from the holotype. At the PETM we also identify “*A. sibaiyaensis*” with 6-9 chambers. This taxon differs from the holotype not only in the number of chambers but also in the wall-texture (Plate 2). In fact, the wall texture of *A. sibaiyaensis* is covered with spiky pustules, which are rare, or absent, on the surface of the multi-chambered species which we refer to as *Acarinina multicamerata* nov. sp. (see taxonomic appendix). We agree that this taxon occurs only during the PETM and not earlier, but not with an assignment to *A. sibaiyaensis*. We do not exclude that this taxon is a morphological variation of *A. sibaiyaensis*, which diverged from the parent species during the PETM, just like *M. allisonensis* appeared to diverge from the main stock of *M. velascoensis* (Kelly et al., 1998). Therefore, we propose to differentiate *A. sibaiyaensis* and *A. multicamerata*, in order to avoid taxonomic and biostratigraphic ambiguities.

Lumping these two morphologically distinct taxa into one species would lead to a loss of stratigraphic resolution. *Acarinina multicamerata* occurs exclusively within PETM beds. *Acarinina sibaiyaensis* and *A. africana* (by some considered as *Morozovella* because of the slightly keeled last chamber(s)) already appeared during the late Paleocene as indicated by the data of El-Naggar (1966). He recorded these taxa from the topmost meters of the upper Paleocene “Middle Owaina Chalk” (= Tarawan Formation) and the lowermost 14 m of the overlying “Upper Owaina Shale” (= Esna Formation) in the Aweina section. This corresponds to Zone P4 and the lower part of Zone P5 (at least Subzone P5a), when compared to more recent studies on this section (Speijer et al. 1996a, 2000; Ouda et al. 2003). Our observations confirm the occurrence of *A. africana* and *A. sibaiyaensis* in Aweina below the P/E boundary (Plate 1). Ouda et al. (2003) observed these taxa below the unconformity at the basis of the calcarenitic bed, which according to earlier studies (Speijer et al. 1996a, 2000; Schmitz et al., 1997) marks the P/E boundary. Our view is further corroborated by recent observations of pre-PETM occurrences of these taxa in ODP Hole 1220, equatorial
Pacific (Norris and Nunes, 2004). In conclusion the widely adopted reference to *A. africana* and *A. sibaiyaensis* as “excursion taxa” is erroneous. *Morozovella allisonensis* and *Acarinina multicamerata* are thus far the only planktic “excursion taxa” exclusively observed in PETM beds.

4 Stratigraphy

4.1 Lithostratigraphy

In the Nile Valley and Eastern Desert (Egypt) the upper Paleocene to lower Eocene marls and shales belong to the Esna Formation, which is intercalated between the limestones of the upper Paleocene Tarawan Formation and the lower Eocene Thebes Formation (Said, 1990). In Sinai, the Tarawan formation is often absent; therefore the entire Paleocene to lower Eocene succession is often referred to as the Esna Formation (see details in Scheibner et al., 2001). Stratigraphy of the Aweina and Qreiya sections were discussed extensively in Speijer et al. (2000), the Dababiya section by Dupuis et al. (2003). We adopt the lithostratigraphic subdivision of the lower part of the Esna Formation as proposed by Dupuis et al. (2003) for the Dababiya section and applied to the Qreiya section by Knox et al. (2003) (Fig. 2). This subdivision consists of Esna unit 1, ranging from the top of the Tarawan Fm. to the base of the PETM beds, in the Nile Valley known as the Dababiya Quarry Beds. Esna unit 1 consists of grey shaley marls. Esna unit 2 comprises the Dababiya Quarry beds and the overlying grey shales and marly shales. In full expression, the Dababiya Quarry Beds are composed of a succession of 5 different beds with upward increasing carbonate content. At the base, DQB1 is dark laminated non-calcareous clay without calcareous foraminifera, whereas at the top, DQB5 is calcarenitic marl, largely composed of foraminifera. The middle part of the Dababiya Quarry beds, particularly DQB3 and the top of DQB2 are rich in apatite, largely in the form of coprolites and fish remains. The Paleocene/Eocene boundary coincides with the base of the clay bed of DQB1 (1.56 m above the base of the DBH section) at Dababiya (Dupuis et al., 2003). In addition to the sharp contact from marl to shale it is characterized by a pronounced shift in $\delta^{13}C$ of organic carbon, thus providing an excellent tool for correlation with deep-sea and terrestrial records spanning the P-E transition. The bio- and chemostratigraphy of these Egyptian localities were documented in Speijer et al. (2000) and Speijer and Wagner (2002). It was pointed out that at Qreiya and Wadi Nukhla a dark brown marl bed rich in TOC, coprolites, fish bones and scales, and foraminifera marks the onset of the PETM. Following the criteria of Wignall (1994) this bed qualifies as black shale and was denoted as such. This bed was not observed at Aweina, thus pointing to an unconformity across the P/E boundary in this section.

Evaluation of results from Egypt in the context of the detailed Dababiya and Qreiya sequence (Dupuis et al. 2003; Knox et al. 2003), indicates that the coprolite rich dark-brown marl bed (“black shale”) observed at Qreiya (Speijer et al. 2000; Speijer and Wagner 2002) corresponds to DQB3. Consequently, this bed does not correspond to the true onset of the
PETM, as considered earlier, but rather to the level with minimum $\delta^{13}C$ values and thus a somewhat later stage during the PETM (Dupuis et al. 2003).

In Wadi Nukhl, Qreiya and Qurtassyat the low-resolution sampling might be the main cause for not identifying all DBQ beds in our records (mainly DBQ1-2 are absent in our data set). The recent studies on Qreiya by Knox et al. (2003), Berggren and Ouda (2003) and Soliman (2003) indicate that this is at least true for the Qreiya section.

Over a large area in Egypt, DQB5 is the most distinct bed within the relatively monotonous Esna succession, especially in weathered outcrops, because in all sections it has anomalously high CaCO$_3$ contents (50-70%) in the lower part of the Esna Formation. This bed corresponds to the bed previously denoted as Esna unit C at Aweina (Speijer et al., 1996b) and more generally as the “calcarenitic bed” (Schmitz et al., 1997b; Speijer et al., 2000), because of its enormous abundance of planktic foraminifera (>10,000 specimens/gram in the size fraction >125 microns). This bed records the return to more positive $\delta^{13}C$ values (Schmitz et al., 1997; Speijer et al., 2000; Dupuis et al., 2003). At Aweina, this equivalent to DQB5 directly overlies Esna 1. DQB1-4 were thus not deposited and/or preserved at Aweina, marking a significant hiatus at the P/E boundary (Speijer et al., 2000).

Ouda et al. (2003) provide a strongly deviating interpretation of the stratigraphic sequence across the P/E boundary at Aweina. These authors suggest that a 1-m-thick interval below the calcarenitic bed records the onset of the CIE. These beds would thus correlate with the lower Dababiya Quarry Beds and instead the upper ones would be missing. The isotopic data consulted for this view were derived from the data presented by Charisi and Schmitz (1995) and Schmitz et al. (1996). However, it has been convincingly shown in these and other publications, including Ouda (2003), that $\delta^{13}C$ records based both on whole rock and Lenticulina spp. show virtually straight vertical lines up to the unconformity, i.e. the base of the calcarenitic bed (Schmitz et al. 1996, 1997; Speijer et al. 1996a, 2000; see also reproduced figs. 2, 4, 7 in Ouda 2003). These values, $\sim$1‰ for whole rock and around -1‰ for Lenticulina spp., fit well within the range of pre-PETM values elsewhere in the region and are much higher than values (-1‰ to -2‰) for whole rock measurements found within the PETM in the region (e.g. Speijer et al., 2000). If the view of Ouda et al. (2003) were correct, the Aweina record should show a negative excursion below the calcarenitic bed (DQB5), followed by an abrupt positive shift at the unconformity. This is clearly not the case. Biostratigraphic data, such as the presence of Acarinina sibaiyaensis and A. africana just below the unconformity (Ouda et al., 2003) cannot be considered as evidence for the opposite view (see above). As a final argument, also the absence of Acarinina multicamerata at Aweina confirms that DQB2-4 are not preserved at this locality. Thus we are confident that the deposits immediately underlying DQB5 at Aweina constitute the top of the Paleocene of Esna 1 unit, not the base of the Eocene. Consequently also the correlation of the P/E boundary at Aweina to other Nile Valley sections, such as G. Kilabiya, G. Qreiya,
and Abu Ghurra (Berggren et al. 2003; Ouda and Berggren 2003; Ouda et al. 2003) needs revision.

In Gebel Duwi, the stratigraphic equivalent to DQB 3 is developed slightly different from Dababiya and Qreiya as a ~20 cm thick fissile pink marl, containing abundant phosphatic peloids and fish remains (Speijer et al. 2000). Underneath this bed, Speijer et al. (2000) observed a 1 cm thick shale bed without foraminifera, overlying a 20 cm thick reddish interval with abundant calcitic pseudomorphs of dolomite rhombs and few foraminifera. It is not unlikely that this interval could in part correspond to DQB1-2. Similar to Gebel Aweina and Wadi Nukhl a calcarenitic bed, correlative with DQB5 is present in the upper part of the CIE. From our data it is not clear whether an equivalent to DQB4 is present at Duwi or not.

In Jordan the studied interval belongs to the pale yellow, light grey chalky and marly sediments, which have been named Muwaqqar Chalk Marl Formation (MCM) Masri (1963). The MCM is rich in gypsum intercalations. It is overlain by the chert-rich chalky limestones of the Umm Rijam Chert Limestone Formation. Within the monotonous marly MCM sediments, a ~1 m thick dark purple bed, partially laminated and rich in fish remains is intercalated. Biostratigraphic data suggest that this bed correlates with DQB3. Besides lithological and sedimentological similarities, this bed is characterized by increased numbers of Acarinina, near absence of Morozovella, the presence of excursion taxa (Morozovella allisonensis and Acarinina multicamerata), and lowered δ13C values.

### 4.2 Biostratigraphy

The studied interval belongs to planktic foraminifera Zone P5 (Berggren et al., 1995), defined as the biostratigraphic interval between the Last Appearance Datum (LAD) of Globanomalina pseudomenardii and the LAD of Morozovella velascoensis. We apply a modified subdivision (Subzones P5a-P5c) of the scheme proposed by Speijer et al. (2000), which consisted of three subzones: Subzone P5a or Globanomalina chapmani Interval Subzone, Subzone P5b or Morozovella allisonensis Total Range Subzone and Subzone P5c or the Globanomalina luxorensis Interval Subzone. Subzone P5b was considered to represent the early part of the PETM. Morozovella allisonensis is common and well preserved in deposits equivalent to DQB3 at Qreiya and Gebel Duwi. We have also observed it in our samples from Dababiya and Qurtayssiat, in DQB3, though not common. Application of this scheme, however, has provided problems, because M. allisonensis occasionally occurs too sporadically (Berggren et al. 2000; Berggren and Ouda, 2003). Instead, Berggren and Ouda (2003) favored the range of the more common A. sibaiyaensis to characterize a subzone correlative with the PETM. Since M. allisonensis is indeed rare at Wadi Nukhl, Dababiya and Qurtassayat, we partly agree with these observations, but as pointed out above, a subzonation based on A. sibaiyaensis, leads to miscorrelations. Instead we propose to define Subzone P5b on the basis of the total range of Acarinina multicamerata.
Fig. 2 Stratigraphic correlation of the localities, arranged along a transect from the deeper localities on the left to the shallowest ones on the right (roughly N-S orientation). Planktic foraminiferal biostratigraphy is used following Berggren et al. (1995); a modified sub-biozonation, in which P5b corresponds to the total range of *Acarinina multicamerata*, is proposed. Gebel Aweina is been vertically exaggerated.

This new Subzone P5b marks DQB2-DQB4 at Dababiya, and DQB3 in the other localities. Within the high-resolution context of Dababiya this subzone represents the middle part of the CIE, i.e. the level where δ¹³C values reach minimum values and start to increase again to a level midway the gradual return to stable values.

In Gebel Qurtassiat, the black shale (DQB3) contains a calcareous nanofossil assemblage indicative of NP10 (presence of *Tribachiatus bramlettei* and absence of *T. contortus*). This bed immediately overlies marls corresponding to Zone NP5, indicating the presence of an expanded hiatus (2004, Eliana Fornaciari, pers. comm.). In the planktic foraminiferal assemblages, just below the PETM an interval of strong dissolution is recorded (probably in Zone P4), constituted mainly by *Igorina*. 
5 Results

5.1 Planktic foraminiferal assemblages

The planktic foraminiferal assemblages in the study area are mainly composed of Acarinina, Morozovella and Subbotina, which together made up >80% (Fig. 3). Igorina, Parasubbotina and Globanomalina are generally <5%. Chiloguembelina and Zeauvigerina always occur in the background (<1%).

Pre-PETM. In the marls below the PETM, Subbotina exhibits maximum values: 13 – 27% at Duwi, ~30% at Dababiya, and up to ~40% at Aweina and Wadi Nukhl. A maximum of 62% is recorded at Qreiya. At Nukhl, Globanomalina is present in higher numbers (~7%) compared to the other localities. Among the surface dwellers, Morozovella is the most abundant genus and it ranges from a minimum value at Qreiya (12%), ~40% at Nukhl, to a maximum at Duwi (~60%). At Duwi, the abundance of Igorina is slightly higher than in the others localities (up to 8%). Acarinina makes up ~27% in Duwi and Qreiya and ~20% in Nukhl. At Aweina a maximum abundance of Acarinina (~50%) occurs just underneath the unconformity at the P/E boundary, where Morozovella decreases to 28%. Striking is the common occurrence of A. sibaiyaensis and A. africana in the uppermost 50cm of the Paleocene at Aweina.

P/B ratios, expressed as %P, generally fluctuate between 35-75% at Aweina and Dababiya (Fig. 4). Just underneath the unconformity at the P/E boundary at Aweina, a peak of 97% is sandwiched between two lower values (45% below and 25% above). The values are more constant at Nukhl (~75%) and Duwi (~65%). At Qreiya a minimum value (6%) is recorded.

Planktic foraminiferal numbers (PFN) range between 150 and 4500 at Duwi (Fig. 4). At Aweina, Nukhl and Dababiya these numbers are lower, between 20 and 300. At Qreiya the lowest value is recorded; only five planktic specimens/g.

Pre-PETM beds contain 40-50% CaCO3 at Duwi, Dababiya and Nukhl, and ~30% in Aweina. Just below the PETM, the values decrease to ~35% at Nukhl and 20% at Qreiya.

From these data we observe that depressed P/B ratios, lower PFNs and low carbonate contents correspond with high numbers of Subbotina, in samples relatively rich in oxidized pyritic burrow fills.

PETM. A major change in the planktic foraminiferal assemblages occurs within the lower part of the PETM. In beds DQB1- DQB2 at Dababiya, no planktic foraminifera are present, except for a relative peak of poorly preserved Acarinina (~90%) in sample DBH 2.3 (bed DQB2), in which A. multicamerata is recorded. At Duwi these beds possibly correspond to 1 cm shale and the underlying dolomitic interval (~20cm). In the other localities these beds are not recorded in our sample sets. Instead, DQB3 and equivalent beds can be traced in all sections except Aweina and are characterized by very high numbers of Acarinina (~80%). In Qurtayssiat, Acarinina is slightly less abundant (~60%), and Subbotina, Parasubbotina and
Globanomalina exhibit higher values (30%, 7% and 6%, respectively), compared to the other sections. In this interval A. multicamerata and M. allisonensis are recorded, of which the former is the major component. Acarinina sibaiyaensis and A. africana also occur, but in low numbers. At Dababiya in sample DBH 3.12 Acarinina decreases (~30%) and Parasubbotina reaches a maximum (~21%).

Maximum P/B ratios (>99%) are encountered at Wadi Nukhl, Duwi and Qreiya, whereas in Gebel Qurtayssiat the P/B ratios decrease (~64%). In DQB2, just one sample contains enough foraminifera to have a reliable P/B ratio (sample 2.3: P/B ratio ~100%); whereas sample DBH 2.72 contains only 10 planktic foraminifera in the whole residue.

![Fig. 3 Relative frequency of planktic foraminiferal assemblages. Gebel Aweina has been vertically exaggerated.](image)

Planktic foraminiferal numbers of the lower PETM beds vary between the sections, but they are generally higher than in the marls below. At Dababiya these values are <10 in DQB2-lower DQB3 and they increase up to ~100 in upper DQB3. These numbers are up to 3,700 at Duwi, ~1,400 at G. Qreiya and ~4,300 at Wadi Nukhl. Only, at Qurtayssiat the value is extremely low (~2/g).

At Dababiya, at the base of DQB1 the carbonate content drops to zero, and this only increases from the lower part of DQB2 upwards. From sample DBH 2.5 onwards the values
increase again to 30%. In DQB3 and equivalents at Dababiya, Duwi and Qurtayssiat, the carbonate content is generally ~40%, and ~50% at Qreiya and Wadi Nukhl.

Above the interval of *Acarinina* dominance in DQB4-5, the planktic foraminiferal assemblages become more diversified, as indicated by the gradual decrease of *Acarinina*, and the increase of the other genera. Specimens of *A. sibaiyaensis*, *A. africana* are rarely found in DQB4-5 at Dababiya and Aweina, whereas *A. multimerata* and *M. allisonensis* do not occur any more. Overall, *Morozovella* ranges between 36-46% and *Subbotina* increases, but the values remain lower than in Subzone P5a (6-17% at Duwi and Aweina). In Aweina and Duwi, *Globoomalina* is more common (<4% and <6%, respectively) than in Subzone P5a.

The P/B ratios in DQB4-5 increase up to 80-95% and the values are fairly constant in each locality. Similarly, the PFNs abruptly increase, between 10,000 (at Aweina) and 15,000 (at Dababiya and Duwi). At Qreiya the numbers are lower, ~1,200 (DQB4). Also the carbonate contents increase in DQB4-5, ranging between 50% (at Aweina), >60% (at Dababiya) and >80% (at Nukhl).

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**Fig.4** Planktic/Benthic ratio (%P), the numbers of planktic foraminifera/gram (PFN) expressed as logarithmic scale and the carbonate content (CaCO\textsubscript{3} %). Gebel Aweina has been vertically exaggerated. CIE indicates the carbonate isotopic excursion.
Post-PETM. Above DQB5, in the post-PETM phase, planktic foraminiferal assemblages continue to diversify in all localities. At Dababiya and Nukhl, Morozovella decreases toward the uppermost part with minimum values on top (21% and 12%, respectively); whereas Subbotina increases (up to 42% in both localities). Opposite trend in Qreiya, where Subbotina decreases and Morozovella increases upwardly. Numbers of Acarinina are ~30 in Nukhl and Dababiya, higher in Qreiya and Duwi (~40%) up to >40% in Gebel Qurtayssiat. Generally the P/B ratios are quite stable between 85-90%, slightly higher in Nukhl (>90%). The numbers of foraminifera are generally quite stable ~1000/g, with a maximum peak in Duwi (~18,000) and a minimum in Nukhl (~90/g). Generally, the carbonate content values are quite stable 30%, higher in Nukhl (~50%). Instead, at Duwi from sample 1033 onwards an interval with lower carbonate content (~20%) is recorded, and interrupted by a ~1.5m-thick interval with no carbonate between samples 1040 and 1042.

6 Discussion

6.1 Avoiding taphonomic pitfalls
The paleoecological significance of foraminiferal assemblages is based on the assumption that the fossil assemblage is a good reflection of the original live assemblage. However, the original ecological assemblage is transformed by a number of processes, of which differential test production (population dynamics) and preservation (taphonomy) are the most important ones (Martin, 1993). Population dynamical processes are difficult to reconstruct in past environments and especially of extinct taxa. Taphonomical distortion of the assemblages is more easily identified (see below) and often is linked to the depositional environment (Loubere and Gary, 1990; Martin, 1993). Despite the transformation from the live assemblage to the dead assemblage, the fossil foraminiferal assemblage still contains important and detailed information of the (time-averaged) environmental conditions during deposition (e.g. Jorissen and Wittling, 1999; Murray and Alve, 1999).
Dissolution of calcareous tests below the lysocline is a well documented and understood phenomenon in deep-sea oceanography and paleoceanography (e.g. Berger, 1970). Dissolution however, is not exclusively restricted to the deep-sea. Also in shallow marine deposits exposed on land partial or complete carbonate dissolution is sometimes encountered. This process may occur during deposition in under-saturated (e.g. brackish) waters, during diagenetic alteration (e.g. with the formation of carbonate concretions), and under the influence of weathering (El Kammar and El Kammar, 1996). In addition, the metabolic consumption of organic carbon from benthic organisms within sediments may contribute to dissolution of calcite even above the lysocline (Freiwald, 1995; Dittert et al., 1999). Also during sample processing in the laboratory dissolution may occur, for instance if sediment containing pyrite-filled tests is disintegrated with the aid of a H₂O₂ solution. Besides the potentially mechanically destructive bubbling from a H₂O₂ inside foraminifera
tests (e.g. Hodgkinson, 1991), dissolution can be a serious problem: the rapid oxidation of pyrite leads to the formation of sulfuric acid, lowering the pH of the solution within the tests. In this way, pyrite-filled tests will partially or fully dissolve. The effect is similar to long-term weathering of pyrite filled test in outcrops. In studies on microfossil assemblages from continental margin deposits partial dissolution is an often ignored problem. The problem becomes apparent when for instance planktic/benthic ratio is employed as an indication for paleodepth and sea-level change. It is well known that tests of planktic foraminifera are generally more susceptible to dissolution than those of hyaline benthic foraminifera (Douglas and Woodruff, 1981). Moreover, in the modern ocean the more solution-susceptible planktic foraminifera species are relatively small in size and have large pores and thin walls, whereas the less solution-susceptible species have large tests with small pores and thick walls and, in general, spinose species are less resistant than the non-spinose one (Bé, 1977).

Also Paleocene planktic foraminifera appear to have dissolved differentially as pointed out by Boersma and Premoli Silva (1983). These authors constructed a solution susceptibility ranking for planktic genera, in environments presumably below the foraminiferal lysocline. In order of decreasing susceptibility: the juveniles of most groups, the large morozovellids, acarininids, small morozovellids, smooth-walled genera, Parasubbotina and Subbotina (spinose taxa). Dissolution during diagenesis is probably controlled more by wall thickness and it acts first on smaller and thinner forms than on more robust taxa, and thus morozovellids are the most resistant ones (Boersma and Premoli Silva, 1983).

There are further ways to assess the amount of dissolution in foraminiferal assemblages. For instance, planktic/benthic ratios can be evaluated against the total number of foraminifera per gram of sediment (PFN). The amount of CaCO₃ in the sediment provides additional information. Where fluctuations between these records coincide, e.g. a drop in P/B ratio together with a drop in PFN and CaCO₃, it is likely that carbonate dissolution has occurred at some step during the generation of the fossil assemblage (e.g. Speijer and Schmitz, 1998). In exceptional situations this association of changes may indicate a real paleoenvironmental change. If so, in shelf settings this should be readily discernable from the composition of the planktic and/or benthic foraminiferal assemblage.

Moreover, weathering in arid regions deeply affects the composition of the sediments. El Kammar and El Kammar (1996), in their study on the shales and marls of the Campanian to Paleocene Duwi and Dakhla Formations in Egypt, establish that the total organic carbon (TOC) of these units diminishes dramatically upon weathering (from an average 7.05% to 0.04%). At the same time, the content of calcite is also drastically reduced by ~60%, due to the production of carbonic acid resulting from the decay of the organic matter during weathering. Therefore, the increase of clay content is only apparent, deriving probably from a depletion of carbonate and organic matter contents. El Kammar and El Kammar (1996) also showed that fresh TOC-rich samples of the Dakhla Formation in the Eastern Desert could only be obtained from caves not from normal exposures prone to weathering. Speijer
and Wagner (2002) and Speijer (2003) measured TOC contents in the Esna and Dakhla Formations, respectively. Beyond the PETM, the TOC content of the Esna Formation is invariably low (0-0.2%), whereas the black shales of the PETM record a peak of TOC (1.5%-2.7%). Also the TOC content in the Dakhla Formation ranges between 0.1-0.3%, and is similar to the outcrop values of El Kammar and El Kammar (1996), whereas the Danian/Selandian black shale bed (“Neo-duwi event”) yields between 0.75% and 2.0% TOC. Considering that there is almost a complete loss of TOC due to weathering in the Eastern Desert (El Kammar and El Kammar, 1996), we argue that the measured TOC contents by Speijer and Wagner (2002) and Speijer (2003) in outcrop samples are probably grossly underestimated. Speijer and Wagner (2002) could not exclude an influence of weathering on the low TOC values and the absence of organic dinoflagellate cysts, but favored a relation to burial effects. The data of El Kammar and El Kammar (1996) demonstrate that weathering is more likely after all. Considering the amount of combusted organic carbon in the studied sediments and the conversion of all pyrite into iron-oxides, it is likely that this had an influence of the amount of carbonate and thus on the foraminiferal composition.

Indeed, also the faunal composition is indicative of different levels of dissolution. In the marls below the PETM of most of the studied sections (Dababiya, Aweina, Qreiya and Nukhl), high numbers of *Subbotina* are often associated with large amounts of oxidized pyritic burrows and concretions. In addition, the planktic/benthic ratio, PFNs and the carbonate content are generally lower than the marls above the PETM. For instance, it is striking that the highest number of *Subbotina* is recorded at Qreiya, associated with the extreme low PFN and P/B ratio. We suggest that all these features together are an index of dissolution, which in general seem to have been more severe before the PETM than after. Therefore, deep weathering might be the principal factor responsible for dissolution in the marls below the PETM. However, we do not rule out that metabolic consumption of the organic carbon from benthic organisms also contributed to this pattern. Conversely, we could also conclude that originally there may have been less organic carbon in P5c sediments. However, not all localities seem to be affected by this phenomenon. For instance, at Duwi the percentage of *Subbotina* is generally lower than in the other localities and the carbonate content higher. Although these differences may primarily relate to the shallower setting, it could also be argued that the deposits at Duwi were less prone to weathering than in the Nile Valley. At Qurtayssiat, weathering seems to have strongly affected also the samples of Subzone P5b, as indicated by lower numbers of *Acarinina*, increased numbers of *Subbotina*, and altogether extremely low numbers of planktic foraminifera.

Conversely, in the uppermost Subzone P5c, *Subbotina* increases again and *Morozovella* decreases. Since P/B ratios, PFNs and carbonate content are generally high, we assume that, in this case, the increased numbers of *Subbotina* represent a primary signal. Since this change in the planktic assemblage coincides with the termination of the PETM, it may points to a termination of the extreme warming phase (Berggren and Ouda, 2003). However,
superimposed on this general trend, at certain levels high numbers of *Subbotina* are still related to lower P/B and PFN, suggesting that probably dissolution occurs.

From these considerations, we stress that assessments of foraminiferal assemblages must take into account that high numbers of *Subbotina* might be an artifact from differential dissolution, and are not necessarily related to ecological factors such as cooling. A combination with P/B ratios, PFNs and carbonate content represents a good tool to discern whether increased *Subbotina* reflects a primary signal or not.

### 6.2 Response of planktic foraminiferal assemblages to the PETM

In Zone P5, in each locality, *Subbotina*, *Acarinina* and *Morozovella* are the major components of the planktic assemblages, whereas *Igorina*, *Parasubbotina* and *Globanomalina* constitute just minor parts. The depth gradient ranging from middle neritic to upper bathyal deposits is not clearly expressed in a corresponding increase in P/B ratios from shallow to deep as could be anticipated on the basis of the relationship between modern P/B ratios and water depth (Van der Zwaan et al., 1990). One reason for this may be the configuration of relatively broad Paleogene shelves compared to those of today; another is that partial dissolution strongly overprints the P/B ratios. Despite this dissolution, it is possible to reconstruct general patterns of water-column conditions. Before the PETM, well-diversified planktic assemblages dominated by *Subbotina*, *Acarinina* and *Morozovella* are indicative of a stratified and well-oxygenated water column. The scarcity of *Chiloguembelina*, considered being a low-oxygen thermocline dweller (Premoli Silva and Boersma, 1988; Boersma and Premoli Silva, 1989) supports this view. At Nukhl, higher numbers of *Globanomalina* are in agreement with the deeper setting of this locality and with colder water compared to the shallower localities. In contrast, at the shallowest Duwi site, the higher abundance of surface dwellers indicates a preference of these taxa for shallower and warmer conditions. In particular, increased numbers of *Morozovella* in the uppermost Subzone P5a are indicative of higher sea-surface temperatures (i.e. Norris, 1996; Berggren and Norris, 1997; Quillévéré and Norris, 2003).

A major change in the assemblages occurs in Subzone P5b. The DQB2-3 beds and their equivalents contain oligotaxic assemblages, dominated by generally poorly preserved *Acarinina*, suggesting high levels of environmental stress in the water column. In particular, *A. multicamerata* is the most common species. *A. sibaiyaensis* and *A. africana* are also present, but very rare. *Morozovella* is almost completely absent during this interval, except for *M. allisonensis* which like *A. multicamerata* suddenly seemed to have evolved. In addition, the impoverishment of the thermocline-dwellers (*Subbotina* and *Parasubbotina*) and the oligotaxic calcareous benthic foraminiferal assemblages (i.e. Speijer et al., 1996b; Speijer and Wagner, 2002) suggest intensification and vertical expansion of the regional Oxygen Minimum Zone.

Above DQB3 and correlative beds (Subzone P5c) the number of *Acarinina* gradually decreases and the population becomes more diversified. In particular, various *Acarinina*
species are present, (i.e. *A. sibaiyaensis*, *A. africana*, *A. coalingensis*, *A. soldadoensis*). All other genera slowly increase again; in particular *Morozovella* completely recovers in numbers and in species diversity. Whereas *M. allisonensis* disappears the *M. velascoensis* and *M. subbotinae* groups return to become the most dominant taxa. Such diversified assemblages combined with an increased number of planktic foraminifera indicate recovery of water-column conditions after the PETM perturbation.

Eutrophy versus oligotrophy during the PETM is still an open debate. It seems that oligotrophy characterized large parts of the deep ocean, whereas along continental margins high-nutrient environments developed. Surprisingly though, the response of planktic foraminiferal assemblages to the climatic perturbation is similar in both settings. *Acarinina* dominates the planktic assemblages in the ocean (Kelly et al., 1996b, 1998; Kelly, 2002) and in deep and shallow Tethyan basins (Arenillas and Molina, 1997; Schmitz et al., 1997a; Lu et al., 1998a; Arenillas et al., 1999; Molina et al., 1999; Pardo et al., 1999; Obaidalla, 2000; Berggren and Ouda, 2003; Ouda, 2003). Various authors (Kelly et al., 1996b, 1998; Arenillas and Molina, 1997; Kelly, 2002) explain this increase as a response to oligotrophic conditions during the PETM, where photosymbiosis may facilitate *Acarinina* to thrive in low nutrients waters. However, other proxies, such as benthic foraminifera (Speijer et al., 1996b; Speijer and Schmitz, 1998; Thomas et al., 2000), calcareous nannofossils (Monechi, 2000), siliceous plankton and organic dinocysts (Benjamini and Sheva, 1992; Crouch et al., 2001; Egger et al., 2003), barium, phosphate, clay-minerals, and TOC records (Schmitz et al., 1997b; Bains et al., 2000; Bolle et al., 2000b; Schmitz, 2000; Speijer and Wagner, 2002) rather indicate eutrophic conditions, related to increased upwelling and/or weathering and run off, particularly in the Tethyan area. For instance, Bolle et al. (2000b) suggest that in the southern Tethys, humid and warm conditions in the hinterland enhanced runoff, supplying plenty of nutrients to the water column, to prevent extreme oligotrophy in the basin. In addition, Speijer and Wagner (2002) propose a paleoceanographic model for this area, suggesting that a combination of inflowing of less oxygenated intermediate water into the epicontinental circulation, combined with intensified upwelling result in severe anoxia on the sea floor. This process resulted in an expanded OMZ and led to the suppression of the thermocline dwellers, such as subbotinids.

Whilst low productivity on the southern Tethyan margin is an unrealistic scenario, we believe that oligotrophy alone cannot be the primary factor controlling the dominance of *Acarinina*. Clearly, the trophic strategy or strategies of this group needs to be investigated more closely. As pointed out by Houston and Huber (1998), the role of photosymbionts in modifying stable isotopic values is not fully understood in living planktic foraminifera; therefore the application of stable isotopes to discriminate symbiotic and asymbiotic taxa in the fossil records is full of uncertainties and suppositions. Additionally, we believe that the relationship between planktic foraminifera and their symbionts during the Paleocene is more intricate than generally asserted, however it probably represents the key to demystify the success of *Acarinina* and the suppression of *Morozovella* at the PETM. It is well accepted
that *Morozovella* and *Acarinina* share similar ecological preferences: they supposedly inhabited the mixed-layer and carried algal symbionts (Pearson et al., 1993; D’Hondt et al., 1994; Kelly et al., 1996a; Norris, 1996). However, among *Acarinina* different species preferred different habitats within the mixed-layer. For instance, the low trochospiral early species of *Acarinina* (prior to 57.0 Ma), probably lived in the deeper, cooler and more mesotrophic part of the mixed-layer (Quillévéré and Norris, 2003). Additionally, Corfield and Norris (1998) suggest that significant carbon isotopic differences may exist between different clades of *Morozovella*; for instance *M. subbotinae* occupied a slightly deeper, cooler and more mesotrophic habitat, than *M. velascoensis* (Quillévéré and Norris, 2003). Therefore the *M. subbotinae* lineage seems to have shared a similar habitat as early species of *Acarinina* (Olsson et al., 1999; Quillévéré and Norris, 2003). Moreover, Kelly et al. (1996b, 1998) show that the oxygen isotopic values of *A. sibaiyaensis* (to us *A. multicamerata*) and of *M. allisonensis* indicate that these taxa encroached into deeper water during the PETM. We consider it highly relevant that during the PETM, the population of *Acarinina* is mainly composed of low trochospiral specimens (e.g. *A. multicamerata*) with higher oxygen isotopic values, more similar to early *Acarinina* species. Similarly, at the Danian-Selandian transition in the same area, we observe a bloom of low trochospiral *Acarinina* during the “Neo-duwi event” (Guasti et al. in prep.), in relation to increased runoff. Also in the Ypresian of the northern Tethyan margin, a peak of *Acarinina* is associated with sapropelic deposits and related to increased productivity (Oberhänsli and Beniamovskii, 2000). From these examples, it can be concluded that peaks of *Acarinina* are also recorded in connection to increased primary productivity in the Tethyan area during the lower Paleogene. This is in disagreement with the supposed affinity of this taxon for oligotrophy.

The importance of the partnership between planktic foraminifera and photosymbionts is amply documented for extant (i.e. Hemleben et al., 1989) and fossil taxa. An impairment of this relationship has been suggested as a cause for the extinction of certain taxa. For instance Kelly et al. (2001) suggest that a progressive deterioration of symbiosis led to the gradual extinction of *Morozovella velascoensis*, probably in connection to a cooling event in the early Eocene. Additionally, during the late middle Eocene, the extinction of the whole *Morozovella* lineage seems to be related to increased surface water productivity and the deterioration of photosymbiotic partnership with algae (Wade, 2004).

The importance of such a partnership is also well demonstrated by modern reef-building corals, which harbor on type of phototrophic dinoflagellates (*Symbiodinium* spp.) or in some cases a suite of symbionts (Rowan et al., 1997; Toller et al., 2001). Corals loose their symbionts and start bleaching when exposed to elevated temperature and high irradiance (Brown, 1997). However, by combining different kind of symbionts, in particular by hosting a symbiont more tolerant to high irradiance and/or temperature, certain corals are protected from bleaching. Additionally, when environmental conditions change, the loss of one or more kinds of symbionts can be rapidly followed by the incorporation of symbionts more suited to the new conditions (Kinzie III et al., 2001). Bleaching is not a phenomenon
exclusively damaging photosymbiotic corals, also reef-dwelling larger foraminifera (i.e. *Amphistegina*) may suffer from this, mainly because of photic stress (Goldberg and Wilkinson, 2004).

In the modern ocean, several species of planktic foraminifera are characterized by symbiotic associations. For instance, the endosymbiont of *Orbulina universa*, *Globigerinoides ruber* and *G. sacculifer* is the dinoflagellate *Gymnodinium bêii* (Gast and Caron, 1996; Rink et al., 1998; Wolf-Gladrow et al., 1999), whereas *Globigerinella aequilateralis*, *Globigerina cristata* and *G. falconensis* host symbiotic chrysophycophytes (Rink et al., 1998). The amount of light availability plays an important role in the abundance and distribution symbionts-bearing planktic foraminifera. For instance in the northern California Current, symbiotic species are more abundant in less turbid (and nutrient-poor) off-shore waters, whereas asymbiotic species dominate in high-turbidity (and nutrient-rich) waters close to the coast (Ortiz et al., 1995). However, symbiotic taxa can also reach high abundance in nutrient-rich waters where turbidity is low and availability of light is high (Ortiz et al., 1995). Furthermore, in the Caribbean Basin increased abundance of *Globigerinoides ruber* is associated to enhance primary productivity (Schmuker and Schiebel, 2002). Hence, high numbers of symbiotic planktic foraminifera do not point exclusively to oligotrophic conditions; instead light availability is often the discriminate factor.

We are aware that it is arduous to demonstrate analogies of host-symbiont relationships between extant and Paleocene planktic foraminifera. However, we aim to point out here that oversimplified concepts of trophic strategies of Paleocene taxa are currently inadequate to explain the distributional patterns associated with the PETM and other transient events. We assume that also Paleocene planktic foraminifera probably were subject to a complexity of relations with their symbionts and different trophic strategies. This is difficult to investigate but should not *a priori* be excluded. In such a view, we could speculate that *Morozovella* and *Acarinina* might have hosted different symbionts. Similar to a bleaching case, we speculate that the relationship between *Morozovella* and its symbionts may have been suppressed at low-middle latitudes during the PETM, in response to environmental stress conditions, including high sea surface temperature. By hosting different symbionts (or having the capability of changing symbionts), low trochospiral *Acarinina* may have been better adapted to these conditions. Hence, a mechanism of preferential elimination of symbionts in *Morozovella* might have been the major factor controlling the suppression of this taxon during the PETM. As a consequence, *Acarinina* could also successfully dominate the oligotrophic open ocean.

It cannot be excluded that the change in the structure of water masses may play a role in this faunal change, however such a scenario on a global scale seems to us unrealistic. Clearly, our ecological inferences are speculative and need further evaluation, but they underscore that the ecology of Paleocene planktic foraminifera is still poorly understood and that the relationships between foraminiferal distributions and biotic and physicochemical
parameters and between the surface dwellers with their symbionts are probably much more complex than currently envisaged.

**Conclusions**

Irrespective of their paleobathymetric positions, the studied sections in the Middle East, are characterized by similar planktic foraminiferal assemblages in planktic foraminifera Zone P5. Within this zone, changes in the assemblages recorded paleoclimatic and paleoceanographic variations, in particular connected to the hyperthermal event at the Paleocene/Eocene boundary:

- In the marls below the PETM (Subzone P5a), the planktic foraminiferal assemblages are affected by dissolution, indicated by high numbers of *Subbotina*, fluctuating P/B ratios and lower numbers of planktic foraminifera per gram of sediment. We stress that assessments of foraminiferal assemblages must take into account that high numbers of *Subbotina* may be an artifact from differential dissolution, and are not necessarily related to ecological factors such as cooling. A combination with P/B ratios, PFNs and carbonate content represents a good tool to discern whether an increase of *Subbotina* reflects a primary signal or not.

- The relatively well diversified planktic assemblages in Subzone P5a are substituted by an oligotaxic *Acarinina* dominated assemblage in response to environmental stress during the PETM. Since biotic and geochemical proxies indicate increased nutrient supply into the basin, due to upwelling and/or enhanced runoff, we argue that the *Acarinina* peak is not indicative of oligotrophic conditions. Instead, we postulate that (mainly low-trochospiral) *Acarinina* could have been better adapted to thrive in stressful surface water conditions than *Morozovella*, because it may have hosted different symbionts.

- Finally, it is inappropriate to subdivide Zone P5 on the basis of the occurrence of *Acarinina sibaiyaensis*, because this taxon occurs in Egypt and off Senegal well before the PETM. Instead, we propose the total range of *A. multicamerata* as biozonal marker of Subzone P5b.
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Taxonomic Appendix A

Acarinina multicamerata sp. nov.
(Plate 2, Fig. 4-6)

Synonymy list:
1996 A. sibaiyaensis El Naggar (Kelly et al.), p. 424 figs. 2-1a to 2-1b.
1998 A. sibaiyaensis El Naggar (Kelly et al.), p. 145 fig. 5c; p. 150 fig. 9D-E (hypotype)
2004 A. sibaiyaensis El Naggar (Arenillas et al., 1994)

Derivatio nominis: The species name multicamerata derives from the numerous chambers in the final whorl which characterized this taxon.

Diagnostic characters: test coiled in a low trochospire, containing 6 to 9 chambers in the final whorl. The chambers are globular and gradually increase in size. Dorsally flattened tests with rounded and lobate peripheral margin. The umbilicus is generally deep. The sutures are radial on both sides and strongly depressed mainly on the ventral side. The aperture is a interiomarginal, extraumbilical-umbilical low elongate arch extending from the umbilicus to the periphery.

Wall texture: non spinose, muricate.

Remarks: A. multicamerata differs from A. sibaiyaensis in several features. A. multicamerata has a higher number of chambers per whorl and the outline is lobate and overall more rounded. The chambers increase more gradually in size compared to A. sibaiyaensis. The wall texture of A. sibaiyaensis is covered with spiky pustules, which are rare on the surface of A. multicamerata. The umbilicus is generally narrower in A. sibaiyaensis, resulting in a more tightly coiled test compared to A. multicamerata.
**Stratigraphic range:** restricted to the Paleocene-Eocene thermal maximum (DQB2-DQB4), in the middle part of Zone P5. Marker species of Subzone P5b.

**Type locality:** Esna Formation at Gebel Duwi, Egypt.

**Distribution:** tropical-subtropical latitudes.

**Origin of the species:** El-Naggar suggested that *A. sibaiyaensis* evolves from *G. perclara* Loeblich and Tappan (1957), which already occurred in the Danian. Instead, Kelly et al. (1998) suggest that *A. sibaiyaensis* (=*A. multicamerata*) evolves from *Acarinina soldadoensis*. Arenillas et al. (2004) propose *Acarinina strabocella* as the ancestor of *A. sibaiyaensis* (=*A. multicamerata*), but this would be in conflict with observations by various authors, who record the highest occurrence of *A. strabocella* in lower Zone P4 (Lu et al., 1998b; Olsson et al., 1999). We suggest that *A. multicamerata* taxon is a morphological variation of *A. sibaiyaensis*, which diverged from the parent species to adapt to different environmental conditions. The stable isotopic signals suggest also a deepening of the living depth of this taxon compared to the ancestor (Kelly et al., 1996, 1998).

**Repository:** Holotype and paratypes will be deposited at the Natural History Museum of London (UK).
Plate 1

1. *Acarinina africana*, umbilical view, holotype.
2. *Acarinina africana*, edge view, holotype.
3. *Acarinina africana*, spiral view, holotype.
5. *Acarinina sibaiyaensis*, edge view, holotype.
8. *Acarinina africana*, Aweina -30- -40

Scale bar: 100µm
Plate 2

1. *Acarinina sibaiyaensis*, umbilical view, holotype.
2. *Acarinina sibaiyaensis*, edge view, holotype
3. *Acarinina sibaiyaensis*, spiral view, holotype.
4. *Acarinina multicamerata*, sp. nov., Gebel Duwi BI3 +12-14
5. *Acarinina multicamerata*, sp. nov., Gebel Duwi BI3 +8-12
6. *Acarinina multicamerata*, sp. nov., Gebel Duwi BI3 +8-12
8. *Morozovella allisonensis*, Qreiya 271185/26
9. *Morozovella allisonensis*, Gebel Duwi BI3 +8-12

Scale bar: 100µm
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CHAPTER VI

The impact of the Paleocene/Eocene Thermal Maximum on foraminifera in the southern Tethys (Dababiya, Egypt)

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CHAPTER VI

The impact of the Paleocene/Eocene Thermal Maximum on foraminifera in the southern Tethys (Dababiya, Egypt)

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Abstract

Benthic and planktic foraminiferal communities were studied in the late Paleocene and early Eocene of the Dababiya section in Egypt. This section hosts the GSSP for the basal Eocene and as such provides a relatively continuous and expanded record across the Paleocene/Eocene Thermal Maximum (PETM). The foraminiferal record is interpreted in terms of paleoecological signals.

The planktic and benthic foraminiferal communities are subdivided in three main faunas indicative for the late Paleocene, middle PETM and the late to post-PETM. The late Paleocene fauna was highly diverse and reached fairly high densities. It was mainly dominated (~50%) by two small taxa: Bulimina cf. thanetensis and Globocassidulina subglobosa, but larger robust trochospiral taxa (e.g., Cibicidoides spp. and Anomalinoidea spp.) were also common in this interval. The planktic community was composed of both deep and shallow-dwelling taxa. These communities are considered to reflect mesotrophic conditions with relatively high productivity and (fluctuating) low oxygen levels.

At the P/E boundary diversity and densities decreased strongly, coinciding with the global level of extinction of benthic foraminifera (BEE) and start of the Carbon Isotope Excursion (CIE). This marked the onset of the PETM and during the first stages of the CIE a non-calcareous laminated clay was deposited under anoxic conditions. The seafloor remained nearly permanently anoxic and a-biotic during this early PETM interval. One sample contained an assemblage of shallow-dwelling planktic foraminifera (dominant taxon: Acarinina multicamerata sp. nov.), an indication that surface waters remained oxygenated during the early PETM.

During the middle PETM very low densities of a low-diverse/high-dominance benthic fauna appeared, indicating occasional re-oxygenation of the basin followed by short periods of repopulation of the benthic environment. Certain taxa were able to cope with these adverse eutrophic conditions by the capacity to rapidly migrate and adaptive reproduction or metabolic strategies (e.g., Anomalinoidea aegyptiacus, Valulineria spp. and Stainforthia spp.). The planktic community started to diversify, although shallow-dwelling taxa remained dominant (Acarinina, Morozovella) indicating poor conditions for deep-dwelling taxa.
The environmental conditions changed strongly during the late PETM and long-term sustainable communities of foraminifera developed under mesotrophic conditions. The diversity and densities of the benthic and planktic faunas first increased strongly, but during the final stages of the late PETM densities and diversity slightly decreased. Planktic faunas remained diverse with both deep and shallow-dwelling taxa. *Bulimina callahani* dominated the benthic assemblage, which is thought to be representative of low oxygen levels and/or high productivity.

1 Introduction

In the Cenozoic the Earth experienced its warmest periods during the late Paleocene and early Eocene times (e.g., Thomas, 1998). The transition from the Paleocene to the Eocene is characterized by a number of exceptional events and it was the start of a very warm period known as the Paleocene Eocene Thermal Maximum (PETM), which lasted for 60,000 years (e.g., Kennett and Stott, 1991). A global drop in $\delta^{13}C$ values of up to 2-3‰ during ~200,000 years, known as the Carbon Isotope Excursion (CIE), marks the onset of the PETM during which global temperatures rose with an estimated 5 to 8 degrees Celsius within a few thousand years (Kennett and Stott, 1991; Zachos et al., 1993; Koch et al., 1995; Corfield and Norris, 1998; Jenkyns, 2003). The climatic changes that took place in this time interval are thought to be a good analogue for the climatic changes the Earth is facing today and perhaps already in the very near future (Dickens et al., 1999). The PETM is so far one the best studied periods in the Earth’s history, in which a very rapid climate change took place. Understanding the PETM can be very important in order to understand the development and response of the atmosphere and biosphere to the strong and rapid climatic perturbations and how restoration of the Greenhouse conditions took place (e.g., Schmitz, 2000).

The explanation for the dramatic climate change during the PETM is sought in the release of a massive amount of methane from gas hydrates (Dickens et al., 1995; Katz et al., 1999; Dickens, 2004). The strong negative shift in $\delta^{13}C$ (CIE) is until today only explainable by the release of the very light methane (~ -60‰ $^{13}C$). However, the trigger responsible for the release of methane is still a point of debate. Explanations range from initial deep-sea warming (Dickens et al., 1995), the impact of a comet (Kent et al., 2003) to volcanism (Eldholm and Thomas, 1993) and a recent study proposes that carbon-rich sediments in the northeastern Atlantic were intruded by mantle material causing an explosive release of methane (Svensen et al., 2004).

The effect of the globally rising temperatures on ocean productivity remains a point of debate. Several oceanic records and particularly the calcareous nanofossils suggest widespread oligotrophy (Kelly et al., 1996; Bralower, 2002), whereas most continental margin records (Speijer et al., 1996b, 1997; Schmitz et al., 1997b; Crouch et al., 2001;
Speijer and Wagner, 2002; Gavrilo
ev, et al., 2003) and also some open ocean records (Thompson and Schmitz, 1997; Bains et al., 2000; Thomas et al., 2000; Stoll and Bains, 2003) suggest an increase in productivity. 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 Oberhansli, 2003; Speijer and Mor
si, 2002), but in the deep sea among the benthic foraminifera a major extinction took place (Tjalsma and Lohmann, 1983; Kennett and Stott, 1995; Thomas, 1998). This benthic foraminifera extinction event (BEE) yields high extinction rates up to 50% in the deep-sea, the highest extinction rates for benthic foraminifera of the past 90 millions years (Tjalsma and Lohmann, 1983; Thomas, 1998). The Paleocene pre-extinction benthic foraminiferal faunas are cosmopolitan and two principal assemblages can be distinguished. The first is the so-called Midway-type representative of continental shelf environments and the second is the Velasco type fauna representative of lower continental slope to abyssal plain environments (Berggren and Aubert, 1975), although some individual taxa had broad bathymetrical ranges (Tjalsma and Lohmann, 1983). Characteristic of both the Midway and the Velasco faunas is that they consist of highly diverse and thick-walled calcareous taxa.

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 unconformities, CaCO₃-dissolution intervals and a poor recovery 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 or post-extinction faunas appear to be less cosmopolitan and a higher differentiation existed in geographical distributions, some general assemblage patterns are identified. For instance, benthic foraminiferal assemblages composed of Nuttallides truempyi and Oridorsalis umbonatus dominate abyssal sites in the North and South Atlantic, Pacific Ocean and are thought to be representative of oligotrophic conditions (e.g., Miller et al., 1992). At bathyal to middle bathyal depths post-extinction faunas show to be dominated by buliminids at various sites in the Atlantic, Pacific and Tethyan regions and these assemblages are thought to be indicative of low oxygen or high productivity conditions (e.g., Thomas and Gooday, 1996; Thomas and Shackleton, 1996). In the southern Tethys the extinction event appears less severe at middle to outer neritic depths and estimated extinction percentages range up to 25% (Speijer, 1994a; Speijer et al., 1997). At outer neritic depths a major turnover took place from a pre-extinction A. avnimelechi-dominated assemblage to a long-term post-extinction assemblage dominated by Bulimina callahani (Speijer and Wagner, 2002). At some neritic sites (paleodepth 150-200m) the assemblage immediately following the extinction level is composed of very characteristic PETM taxa like Anomalinoides aegyptiacus, A. zitteli, Valvulineria spp. and Stainforthia spp. (e.g., Speijer et al. 1996a; Speijer and Schmitz, 1998; Speijer and Wagner, 2002). This low-diverse and high-
dominance fauna is interpreted as being representative of a heavily disturbed environment, in which highly eutrophic conditions (low oxygen/high productivity) prevail. The southern continental margin of the Tethys Ocean offers good and well-preserved records of the Paleogene in North Africa (e.g., Ouda, 2003). These records enable micropaleontological research on a wide range of organisms, such as benthic foraminifera (Speijer et al., 1994b), planktic foraminifera (e.g., Berggren and Ouda, 2003; Guasti and Speijer, submitted), ostracodes (e.g., Speijer and Morsi, 2002) and nannoplankton (e.g., Youssef, 2003). Further a number of studies focused on the geochemical and mineralogical data in the Paleogene deposits of the southern Tethys (e.g., Charisi and Schmitz, 1995; 1998; Knox et al., 2003). The global boundary stratotype section and point (GSSP) for the Paleocene/Eocene boundary is defined within the Dababiya Quarry section (Egypt), near Luxor in the Nile Valley (Dupuis et al., 2003). The Dababiya Quarry beds offer the possibility to combine numerous research fields in one section and are further of great importance since they compose one of the most expanded marine successions known today of the PETM (Ouda and Aubry, 2003). The estimated paleodepth at Dababiya during the late Paleocene and early Eocene in Dababiya is 150 to 175 m deep (Dupuis et al., 2003).

The expanded Dababiya section offers a good opportunity to identify and unravel in more detail the climatic events and developments that took place during the PETM. In order to reconstruct the paleoenvironment at a higher resolution across the P/E boundary and in the PETM, we will focus in this study on benthic foraminifera, planktic foraminiferal and lithological data as well. The faunal, sedimentological and chemical data are thought to present detailed recordings of the climatic perturbations that occurred during the CIE and PETM. The $\delta^{13}C$ record supports that the Dababiya section comprises a fairly continuous record of the CIE (Dupuis et al., 2003).

2 Material and Methods

2.1 Location

The Dababiya section (25°30'N, 32°31'52"E) is located on the right (east) bank of the upper Nile Valley (Fig. 1a). This section is a composite section, which is composed of four partially stratigraphically overlapping sections and this study is focused on one of them; the Dababiya H section (Dupuis et al., 2003). The Dababiya H section is designated as the GSSP of the Paleocene/Eocene boundary (Fig. 1b). The previously described biostratigraphy (Berggren and Ouda, 2003) is modified by applying here a new subzonation of planktic zone P5, which is introduced in Chapter V.
2.2 Lithology and stratigraphy

A detailed description of the lithology of the Dababiya H section is given in Dupuis et al. (2003) and the stratigraphic log in Figure 2 is based on this paper. The base of the Dababiya H section is composed of the upper ~2 m of the Esna 1 unit (~1.85 to 0 m). It is composed of marly shales with carbonate contents of 25-50%. The base of the Esna 2 unit is composed of a set of five beds: the Dababiya Quarry beds (DQ-beds). The P/E boundary is characterized by a basal dark grey clay, overlain by phosphatic, calcareous shales and calcarenitic limestones. The Dababiya Quarry 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 (Dupuis et al. 2003). Five beds are distinguished lithologically:

- DQ-bed 1 (0-0.63 m): 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): light-colored laminated phosphatic shale with some coprolites and many phosphate inclusions and 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): light-grey marly calcarenitic limestone, high carbonate content (~70%).

Above the DQ-beds the Esna 2 unit in the upper part of the Dababiya H section (3.68-4.58 m) is rather dark, clayey and with low carbonate content (< 30%). The position of the samples used in this study is shown in Figure 2.
2.3 Sample preparation

About 50 gram of rock/sediment was taken from each sample from the Dababiya H section and dried at 60 C for 24 h. Afterwards, the samples were soaked in a 0.5 M Na₂CO₃ solution and left for a couple of days. When the samples were disintegrated they were washed wet over a 63 µm sieve and then dried at 60 °C. For some samples the soaking treatment was repeated when still sediment was aggregated during sieving. After drying the residues were sieved over 63, 125 and 630 µm. The fraction of 63-125 and 125-630 µm were studied separately. When possible of each sample in both size fractions at least 200 specimens were counted. In the case of high densities splits of at least 200 specimens (excluding non-calcareous agglutinated foraminifera) were made by using an Otto microsplitter.

Fig. 2 Stratigraphical and lithological column of the Dababiya H section (modified from Dupuis et al., 2003). The location of the samples is indicated in the meter-scale by the grey triangles. Legend: 1) marls, 2) shales, 3) brown phosphatic shale with coprolites, 4) light-colored phosphatic shale, 5) calcarenite. Subzonation of P5 proposed in Chapter
2.4 Taxonomy
Most species were identified at the species and some at the generic level and we followed the taxonomy as described in Speijer (1994b). In total more than 85 taxa were recognized of which about 40 are discussed in more detail. A large group of agglutinants and very diverse nodosariids were lumped. A group of, mostly poorly preserved and difficult to determine non-calcareous agglutinants (i.e., *Trochammina* spp., *Haplophragmoides* spp., *Bathysiphon* etc.) were excluded from the rest of the foraminifera in all calculations and analyses. The frequency and distribution data of this group is discussed separately. Other calcareous taxa were lumped generically because of low density or by high degree of morphological variability (e.g., *Nuttallides* spp., *Gyroidinoides* spp., *Pullenia* spp., etc.). A single specimen of *Valvulineria* sp. was encountered in the CIE/PETM interval (Speijer and Ernst, in prep).

2.5 Statistics
Principal component analysis (PCA, Canoco 4.0, GLW-CPRO, Ter Braak and Šmilauer, 1998) was used to identify in multivariate space by indirect gradient analysis relationships between the taxa in the samples. Frequency data was log-transformed before analysis. A PCA was run for each of the two separate size fractions (63-125 and 125-630 µm) and for the combined size fraction of 63-630 µm.

3 Results

3.1 General (paleoenvironmental) indices
General environmental indices are graphically summarized in Figure 3, such as number of benthic and planktic foraminifera per gram sediment, Shannon Diversity, Planktic/Benthic foraminiferal ratios and the $\delta^{13}C$ and CaCO$_3$ content of the bulk sediment (Dupuis et al., 2003). The negative excursion of the $\delta^{13}C$ record indicates the CIE interval. The CaCO$_3$ content in the section is on average around 35% and in the early CIE/PETM interval calcium carbonate is absent. In the late PETM values peak in DQ-bed 5 up to 66%, but the CaCO$_3$ content decreases in the post-PETM to ~25%. The variation of the number of benthic foraminifera per gram sediment shows in both smaller and larger size fractions a very similar pattern (Fig. 3). In the Esna 1 unit numbers are relatively constant but at the PE boundary a strong decrease is observed. In the CaCO$_3$ dissolution interval (from DQ-bed 1 to the base of DQ-bed 3) benthic foraminifera are almost totally absent except for some siliceous agglutinated forms (see section on non-calcareous agglutinated foraminifera). In DQ-bed 3 benthic foraminiferal densities increase strongly to a peak in DQ-bed 5 of almost 800 specimens per gram sediment in the 125-630 µm fraction, and almost 2500 specimens per gram sediment in the 63-125 µm fraction. Foraminiferal densities remain high in DQ-bed 5 but steadily decrease to 141 and 445 specimens per gram for the, successively, 125-630 and 63-125 µm fractions in the Esna 2 unit above the DQ-beds.
The Shannon diversity of the total benthic assemblage (63-630 µm) is very constant in the Esna 1 unit. At the P/E boundary, however, a strong decrease in diversity is observed. In DQ-bed 3 diversity initially even decreases further but a gradual increase is observed from the upper part of DQ-bed 3 towards the base of DQ-bed 5, where diversity is highest. In the post-PETM above the DQ-beds diversity decreases slightly.

The number of planktic foraminifera shows a very similar pattern as observed in the benthic foraminifera, but densities are generally higher than the benthic foraminifera. Comparing the planktic and benthic foraminifera in the P/B ratio, values average about 50% in the Esna 1 unit. P/B ratios increase strongly in the DQ-beds above the CaCO₃ dissolution interval and are on average higher than 85%. In the Esna 2 unit above the DQ-beds the P/B ratios decrease again to about 55%.

**Fig. 3** Graphical summary of the benthic foraminiferal numbers per gram for the two studied size fractions, the Shannon diversity of the total benthic foraminiferal fauna (63-630 µm), planktic foraminiferal numbers per gram, the planktic/benthic foraminiferal ratio for the > 125 µm fraction and the δ¹³C and CaCO₃ curve for the Dababiya H section (after Dupuis et al., 2003).
3.2 Benthic foraminifera
The benthic foraminifera are counted and studied separately in the size fractions 63-125 and 125-630 µm. The results are presented separately for the most abundant taxa in both size fractions and finally these results are combined to present the patterns for the most abundant taxa in the total assemblage (63-630 µm). The importance of studying the smaller size fraction is demonstrated by its share in the total foraminiferal community (63-630 µm), which in all samples is at least 75%, but in many samples they constitute over 90 to even 98 % of all foraminifera larger than 63 µm (Fig. 4).

**Fig. 4** Comparison of the relative share of the 63-125 µm in the total foraminiferal communities (63-630 µm) vs. the density patterns of both size fractions (63-125 µm and 125-630 µm).

**63-125 µm**
Certain taxa are mainly or exclusively encountered in the Paleocene (Fig. 5: *Cibicidoides pseudoacutus*, *Angulogavelinella avnimelechi*, *Anomalolinoides affinis*, *Sporobulimina eocaena*) and others are found quite evenly distributed in both the Paleocene and Eocene samples (Fig. 5: *C. rigidus*, *Bulimina midwayensis*, *A. cf. midwayensis*, *C. succedens*, *Loxostomoides applinae*, *Neoeponides lunatus*, *Gyroidinoides* spp., *Osangularia plummerae*, *Spiroplectinella dentata/esnaensis*). The very dominant taxa in this size fraction (*Globocassidulina subglobosa* and *Bulimina cf. thanetensis*) are more dominant in the late Paleocene, although they remain very frequent in the middle to late PETM. A small group of taxa are found very dominant in the middle PETM just above the interval affected by carbonate dissolution (A.
aegyptiacus, Lenticulina spp., Stainforthia spp., Valvulineria scrobiculata). A large group of taxa are found in the Paleocene deposits but become more dominant when progressing from the middle to late PETM (DQ-beds 3-5) to the post-PETM 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 frequent.

125-630 µm
The general patterns as observed in the smaller size fraction are also reflected in the larger size fraction (Fig. 6). However, taxa that are very dominant in the smaller size fraction in both the late Paleocene and Eocene are not encountered in this size fraction. In the late Paleocene Cibicidoides pseudoacutus is one of the most abundant taxa, but almost all taxa are quite evenly distributed throughout the Paleocene interval. However, at the boundary a distinct change is observed and Anomalinoides cf. midwayensis and Lenticulina spp. become dominant. In the DQ-beds 3 and 4 Lenticulina spp. (>50%), but also A. aegyptiacus, A. zitteli, C. pharaonis/decoratus and V. scrobiculata become dominant. A distinct peak of Spiroloculina sp. is observed in DQ-bed 5. From DQ-bed 3 on Bulimina callahani becomes more and more dominant and in the Esna 2 unit above DQ-bed 5 its relative abundance peaks to 25% of the total assemblage.

63-630 µm
The twenty-four most abundant taxa are selected for the combined results of the smaller and larger size fraction (Fig. 7). A subdivision is made in distinct faunal assemblages representative of the late Paleocene, early PETM (DQ-beds 1- middle of DQ-bed 3) middle PETM (middle of DQ-bed 3 to DQ-bed 4) and the late PETM (DQ-bed 5) to post-PETM. First, the late Paleocene fauna is dominated by the smaller taxa Bulimina cf. thanetensis and Globocassidulina subglobosa and to a lesser degree by Neoeponides lunatus. Larger and very abundant taxa are Cibicidoides pseudoacutus, C. rigidus, Anomalinoides affinis. Foraminiferal markers for the Paleocene are Angulogavelinella avnimelechi and Gavelinella beccariiformis that become extinct in the Eocene.

At the boundary foraminiferal numbers are very low and thick-walled Anomalinoides cf. midwayensis and Lenticulina spp. are dominant (sample DBH 0.00). From the Paleocene/Eocene boundary and in the early PETM, the base of DQ-bed 1, until the middle of DQ-bed 3, calcareous benthic foraminifera are absent. In part of the middle PETM interval (DQ-beds 3-4) a small group of taxa forms a distinct assemblage: A. aegyptiacus appears and becomes very dominant together with Lenticulina spp and Valvulineria scrobiculata. In some samples Stainforthia spp. and Bulimina farafraensis are also abundant. Some smaller taxa (Bulimina cf. thanetensis and Globocassidulina subglobosa) also are present in relatively high frequencies.

From DQ-bed 5 the faunal composition changes into the so-called late to post-PETM assemblage: Bulimina callahani, Oridorsalis plummerae, Tappanina selmensis and
Cibicidoides pharaonis/decoratus become very abundant. Other common taxa in this assemblage are *A. zitteli*, *Turrilina brevispira*, *Spiroloculina* sp., *V. depressa* and *V. planulata*.

Fig. 5 The results of the 63-125 µm fraction: relative distribution patterns of the 32 most common taxa.
Fig. 6 The results of the 125-630 µm fraction: relative distribution patterns of the 36 most common taxa.
Fig. 7 The combined results of the 63 to 630 µm fraction: total relative distribution patterns of the 24 most common taxa.
3.3 Non-calcareous agglutinated foraminifera

In the previously presented results the group of non-calcareous agglutinated foraminifera is not taken into account. This difficult taxonomic group consists of for example *Trochammina* spp., *Haplophragmoides* spp. and *Bathysiphon* spp., which are often poorly preserved and therefore removed from the analyses with the rest of the assemblage. The relative share in the total benthic foraminiferal assemblage and absolute densities are presented in Figure 8. High densities of non-calcareous agglutinated foraminifera are mainly encountered in the Esna 1 unit and can reach as many as 80 specimens per gram sediment. Towards the P/E boundary numbers decrease strongly and absolute numbers remain very low except two peaks in the DQ-beds 3 and 4. Their relative frequency as part of the total foraminiferal assemblage peaks in the early to middle PETM interval (DQ-beds 1-4) and very marked above the P/E boundary (DQ-bed 1,2) up to 100% because of the lack of calcareous foraminifera. Relative scores are much lower or minimal in the late Paleocene and late to post-PETM beds (DQ-bed 4 and younger).

![Figure 8](image_url)

Fig. 8 Distribution data of the group of non-calcareous agglutinants. The relative share of this group as part of the total number of foraminifera is compared with the actual number of specimens per gram sediment.
3.4 Planktic foraminifera

Planktic foraminifera were counted in the fraction >125 µm (Fig. 9). The assemblage is mainly composed by Acarinina, Morozovella and Subbotina, which together make up >85% of the total planktic assemblage in the late Paleocene (Esna 1). Subbotina reaches >30%, Morozovella is the dominant surface-dweller taxon (up to 40%), whereas Acarinina does not reach percentage >20%. Frequencies of Igorina, Parasubbotina and Globanomalina are generally less than 5%. Chiloguembelina and Zeauvigerina occur only rarely (<1%).

In the early PETM interval (DQ-bed 1 to the middle of DQ-bed 3) planktic foraminifera are absent, except for a peak of poorly preserved Acarinina (~90%) in the lower part of DQ-bed 2, in which A. multicamerata sp. nov. is the main component. During this peak, Morozovella is almost absent. A. sibaiyaensis and A. africana also occur, but in low numbers. In the middle PETM (top DQ-bed 3) Acarinina is still the dominant taxon (~80%), except in the sample at 1.55 m where it decreases (~30%) and Parasubbotina and Subbotina briefly increase (~21% and 24%, respectively). During the middle PETM interval Morozovella starts to recover and in the interval between 1.68m to 1.93m M. allisonensis is recorded.

![Fig. 9 Planktic foraminiferal distribution data: the relative patterns are shown for the 6 most abundant genera.](image-url)
In the late PETM (DQ-beds 4-5), the planktic foraminiferal assemblages are more diversified, as indicated by the gradual decrease of *Acarinina* and the increase of other genera. For instance, *Morozovella* increases up to 40% and *Subbotina* to 15%. *A. multicamerata* and *M. allisonensis* do not occur any more. Above DQ-bed 5, in the post-PETM phase, planktic foraminiferal assemblages continue to diversify. *Morozovella* decreases toward the uppermost part with minimum values on top; whereas *Subbotina* increases. Numbers of *Acarinina* are ~30%.

### 3.5 Other observations

In the late Paleocene Esna 1 beds high densities of pyritized burrows are encountered in the samples. Also at the P/E boundary many pyritized burrows are encountered in combination with high numbers of fossilized parts of fishes (e.g., bones, teeth, jaws). In the early PETM phosphate nodules are encountered and pyritized burrows and fish rests remain very abundant. Also fine white gypsum veins are found in the early PETM. In the middle PETM the numbers of burrows and fish remains decrease and in the late PETM they become rare or absent.

### 3.6 Principal Component Analysis

Principal component analyses were performed on three separate data sets: for the 1) the 63-125 µm, 2) the >125-630 µm and 3) the 63-630 µm size fractions (Fig. 10). Here we will present only the data for the 63-630 µm fraction, since this analysis contains all information found in the separate analyses of the smaller and larger fractions. The PCA-analysis offers a good method to graphically summarize faunal patterns in two dimensions of the distribution and abundances of 85 species in 23 samples. The five taxa loading most positively or negatively in each analysis are listed in Figure 10. Appendix 2 presents all species and sample scores for the 63-630 µm analysis.

Sixty-three percent of the variance observed in the data is explained by the first two PCA-axes (1st axis 39.0%, 2nd axis 23.9%). The first PCA-axis distinguishes the middle PETM fauna from the other intervals and also a marked difference is observed between the late Paleocene fauna and the late to post-PETM faunas. The second PCA-axis separates the late PETM to post-PETM fauna from the late Paleocene and middle PETM faunas.

The first PCA-axis is most positively loaded by *Anomalinoides aegyptiacus* and *Valvulineria scrobiculata* and the most negative loadings are by *Cibicidoides pseudoacutus* and *Anomalinoides affinis* (Fig. 10). *Bulimina callahani* and *Turrilina brevispira* have the highest positive loadings for the second PCA-axis, whereas *Anomalinoides aegyptiacus* and *Bulimina cf. thanetensis* have the most negative loadings (Fig. 10).
Fig. 10 Results for the first two axes of the Principal Component Analyses for the total foraminiferal community (63-630 µm).

4 Discussion

The basic assumption in paleoreconstructions is that fossil assemblages truthfully mirror the original biocoenosis and underlying environmental signals. However, fossil communities and assemblages contain time-averaged signals, which actually could mainly be driven by contrasts in (temporal) environmental variations. Living assemblages are modified during the transformation to a dead/fossil assemblage by processes that vary strongly between taxa and over time: differences in population dynamics, and taphonomical differences between various environmental settings (Loubere & Gary, 1990; De Stigter et al., 1999; Jorissen & Wittling, 1999; Martin, 1999). Population dynamical effects are difficult to interpret with most taxa being extinct, but information from extant relatives or populations can be used to interpret faunal patterns. Taphonomical factors such as CaCO₃ dissolution are much easier identified in the fossil record (e.g., Martin, 1999). For instance in the late Paleocene interval P/B ratios are lower and in the marls of the Esna 1 unit many oxidized pyritic burrows and tests are encountered. Also the high number of the planktic foraminifer Subbotina might indicate partial dissolution of the foraminiferal assemblage (Chapter V). Therefore, we approach the resulting faunal patterns with great caution.
A summary of the benthic foraminiferal patterns in other Tethyan sections in the late Paleocene to early Eocene is given by Speijer and Ernst (in prep) and therefore we will focus here in more detail at the paleoecological implications of the late Paleocene, early, middle and late to post-PETM benthic foraminiferal assemblages of the Dababiya H section. Since the Dababiya H section appears the most expanded and relatively continuous section encompassing the CIE identified so far, it contains important information on the events in the Southern Tethys during this interval, which is partly missing in other discontinuous sections in the region (Ouda, 2003; Speijer and Ernst, in prep) and in other areas of the world (e.g., Thomas, 1998).

The PCA analysis and distribution patterns point at a subdivision in four different faunas typical for the late Paleocene, early CIE/PETM (although the ending of the PETM is not clear), middle PETM and late to post-PETM faunas (Fig. 10). Subsequently, these faunas and the ecological implications are separately discussed.

4.1 Late Paleocene fauna

The late Paleocene pre-extinction fauna in Dababiya is mainly composed of taxa characteristic of outer neritic conditions in the Southern Tethys (e.g., Speijer, 1996). Some bathyal taxa (e.g., Gavelinella beccariiformis and Pullenia coryelli) are encountered in (very) low densities and are markers for the pre-extinction faunas and they disappear after the extinction level. The pre-extinction fauna is dominated by Globocassidulina subglobosa,
*Bulimina* cf. *thanetensis*, *Cibicidoides* spp. and *Anomalinoideos* affinis. The assemblage is named after the presence of relatively high densities of the marker taxon *A. avnimelechi*, which extensively occurs in the neritic southern margin of the Tethys. 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 *Globocassidulina subglobosa* could 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). The presence of smaller and thin-walled genera (e.g., *Pulsiphonina*, *Neoeponides*) might indicate CaCO3 corrosive conditions (Thomas, 1998), which could be in agreement with low oxygen conditions as illustrated by the sometimes-high densities of pyritized burrows encountered in the Esna 1 beds. Non-calcareous agglutinated taxa reach high densities in the late Paleocene, which can also point at CaCO3 corrosive conditions. Planktic foraminifera in this interval include highly diverse deep and shallow dwelling taxa, showing no evidence for long-term stratification of the water column.

Just below the level of extinction the diversity and foraminiferal densities start to drop and the poor preservation of foraminiferal tests reflect increased CaCO3-dissolution. Thick-walled taxa such as *Lenticulina* spp. and *Anomalinoideos* cf. *midwayensis* peak just below the level of extinction and the environmental conditions apparently start to change, with a strong negative effect on the benthic faunas.

### 4.2 Early PETM fauna

The start of the CIE in Dababiya, coeval with the start of the PETM, can be subdivided in three intervals and the first, the early PETM, starts at the extinction level and covers DQ-bed 1 to the lower part of DQ-bed 3. At the level of extinction the lithology changes drastically into a non-calcareous laminated clay with phosphate nodules at the base. This is very characteristic of anoxic sediments where no bottom fauna is present (e.g., Wignall, 1994). Even non-calcareous agglutinated taxa disappear in this interval, indicating that conditions indeed appear to have been very hostile. The water column does not appear to have been completely anoxic, at least not throughout, since planktic foraminifera have been preserved in a level at the base of DQ-bed 2. Perhaps conditions were even at the seafloor re-oxygenated during a very short period in this DQ-bed 2, since very low numbers of small (<125 µm) *Anomalinoideos aegyptiacus* and a single specimen of *Bulimina* cf. *thanetensis* were found, although this could be an artifact by reworking of older sediments.

The CaCO3 corrosive conditions prevailing at the seafloor will have caused to dissolve the downward transported shells of dead planktic foraminifera that lived in the (oxygenated) surface waters. The planktic genera encountered in the level of DQ-bed 2 are interpreted as shallow-dwelling taxa, inhabiting the mixed layer (>90 % *Acarinina*). *Acarinina* is indicative for oligotrophic conditions, but here the dominant taxon is *A. multicamerata*, which is thought to be able to flourish under nutrient-rich conditions (Chapter V). *Acarinina* probably
hosted symbionts (Pearson et al., 1993; Norris, 1996), which would have helped this taxon to thrive in oligotrophic water. However, it seems that certain species could also stand nutrient rich waters.

The anoxic conditions at the sea floor facilitated a better preservation of fish remains sinking to the seafloor. The abundant fish fossils in this interval could indicate nutrient-rich and oxygenated surface waters, but the question remains whether these fossils are not transported from other areas.

The strong dissolution of CaCO₃ could have been caused by increased CO₂ levels by the release of methane associated with the melting of gas hydrates and this might even been increased by a combination of anoxia and high organic matter load linked to the stratification of the water column. Stratification might have been the result of increased continental runoff and input of continental nutrients, which could have lead to an increase of the productivity in the surface waters. This is substantiated by the clay mineralogy (Fig. 11), which shows a peak in kaolinite in this interval (Dupuis et al., 2003) and an indication of intense chemical weathering and continental runoff.

The environmental conditions at the seafloor were very hostile by the long-term anoxic conditions that prevailed and during which benthic faunas were unable to survive. Perhaps conditions occasionally changed shortly with re-oxygenation of the seafloor but these periods lasted not long enough to sustain foraminiferal faunas or other benthic organisms on the long term.

4.3 Middle PETM fauna

During the middle PETM (DQ-beds 3-4), in which faunal conditions improved, pioneering low-diverse benthic faunas (i.e., Anomalinoideae aegyptiacus, Valvulineria scrobiculata, Stainforthia spp.) are encountered, showing overall very low densities during this interval. The low-diverse fauna appears to be indicative for stressful conditions with low oxygen levels and high productivity (Speijer et al., 1996b; Speijer and Schmitz, 1998; Speijer and Wagner, 2002). 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 (e.g., northern Adriatic Sea; Duijnste, et al., 2004). The low densities in the middle PETM indicate that the anoxic conditions lasted continuously throughout this interval. If re-ventilation of the water column took place during this interval, these periods were probably very short, since modern benthic foraminifera specialized to live in highly eutrophic environments are able to survive anoxic periods of more than two months (Moodley et al., 1997; Ernst et al., in press). General characteristics of such stress-faunas are relatively small, thin-walled, sometimes highly porous and low-diverse faunas (Bernhard and Sen Gupta, 1999). These faunas are often composed of taxa with different life-strategies (Duijnste, et al., 2003). For example, some taxa of such a fauna are opportunists (or ruderals): capable of responding immediately to favorable conditions by changing for
instance reproduction rates, whereas other taxa are stress-resistant, capable of surviving (relatively) extreme environmental conditions, reflecting low reproductive rates. Here, the opportunistic taxa could be represented by *Anomalinoide aegyptiacus*, *Valvulineria* spp., *Stainforthia* spp., *Bulimina farafraensis* and *Lenticulina* spp. Survivors are for instance *Bulimina* cf. *thanetensis* and *Globocassidulina subglobosa* which in this phase appear relatively abundant in the smaller fraction. The eutrophic conditions in this interval could be related to high continental runoff, which could be substantiated by the fossilized parts of wood that constitute a large part of the total organic matter in this interval (Dupuis et al., 2003). The planktic foraminiferal genera *Acarinina* and *Morozovella* dominate in this interval and they are shallow dwelling taxa, inhabiting the mixed layer. Towards the end of DQ-bed 4 the diversity and the density of both benthic and planktic foraminifera starts to rise very strongly.

### 4.4 Late to post-PETM fauna

During the late PETM (DQ-bed 5) the diversity and density of both planktic and benthic foraminifera reach high levels. The conditions were very favorable for the productivity of foraminifera with sufficient nutrient input and without severely low oxygen levels. Deeper-dwelling planktic foraminifera become more abundant and indicate well-ventilated conditions in the basin.

The benthic faunas reflect mesotrophic conditions, with relatively high productivity, resembling pre-extinction conditions in the late Paleocene, illustrated by the peak of *Globocassidulina subglobosa*. The fauna becomes more diverse and *Bulimina callahani* increases in abundance. Further, the highest benthic and planktic foraminiferal densities are found during the late PETM. Other taxa appear in high frequencies; such as the miliolid *Spiroloculina* spp.. This could indicate well-oxygenated conditions since Recent miliolid faunas are associated with high oxygen levels (e.g., Jannink, 2001). Another example is *Tappanina selmensis*, a taxon regarded as opportunistic and capable of rapid migration (Thomas, 1998). Further *Cibicidoides pharaonis/decoratus*, *Anomalinoides zitteli*, *Turrilina brevissira* and *Valvalabamina planulata* are abundant in the PETM but frequencies decrease in the post-PETM interval. However, comparison with other sections (Speijer and Ernst, in prep) is necessary to interpret these changes since the post-PETM record is very short here.

Species (*Bulimina callahani*, *Oridorsalis plummerae*, *Valvalabamina depressa*) indicative for deeper and more open basin conditions (Speijer and Schmitz, 1998) become more abundant in the post-PETM interval and diversity decreases slightly compared to late PETM. The dominance of *Bulimina callahani* could indicate that low oxygen-high productivity stress may have increased again; a development comparable to that of other continental margin sites in the world with buliminid-dominated faunas (Thomas, 1998). The planktic assemblage becomes less dominated by shallow-dwelling genera and deeper-dwelling taxa become more abundant so the ventilation of the water column increased. In the uppermost Subzone P5c, *Subbotina* increases again. Since this change in the planktic assemblage
coincides with the termination of the PETM, it could point to a termination of the extreme warming phase (Berggren and Ouda, 2003). The post-PETM record of Dababiya is however limited and long-term trends cannot be interpreted.

5 Summary

The overall environmental trend observed in the southern Tethys by summarizing all paleoenvironmental indicators of the Dababiya section (Fig. 12), indicates a strong impact on the foraminifera by the environmental perturbation caused by the PETM. The late Paleocene mesotrophic conditions changed into extreme eutrophic and anoxic conditions during the early PETM as a net result of increased temperature, enhanced river discharge and sea level fluctuations. Bottom life was not possible until the middle PETM when occasional re-ventilation of the water column enabled opportunistic or 'ruderal' benthic foraminiferal faunas to colonize the basin. The fluctuating conditions were not good enough to sustain these faunas over longer periods and foraminiferal densities remain very low. During the late PETM conditions become more constant and favorable for both benthic and planktic faunas. The strong increase in diversity and foraminiferal densities indicate moderate to good ventilation and moderate productivity. During the post-PETM period the sea floor experienced oxygen stress and/or higher organic matter fluxes, indicated by the buliminid dominated benthic assemblage.

Fig. 12 Summary of all the paleoenvironmental indicators in this study
A record of the early and middle PETM, as observed in Dababiya, is missing in other sections in the southern Tethys (Speijer and Wagner, 2002; Speijer et al., in prep). It appears that mainly late PETM DQ-bed 5 (and in some cases DQ-bed 3) is deposited and preserved in most sections in the region and faunal assemblages in sections located nearby (e.g., Speijer et al., 1996a; Speijer and Schmitz, 1998) show very similar patterns. For instance, in Gebel Aweina the bed corresponding to the DQ-bed 5 is also dominated by *Bulimina callahani* and distinct peaks such as *Oridorsalis plummerae*, *Spiroloculina* and *Tappanina selmensis* are recorded here as well (Speijer et al., 1996a; Speijer and Schmitz, 1998).

**Conclusions**

The late Paleocene to early Eocene in Dababiya can be subdivided in 4 intervals, each with distinct benthic and planktic foraminiferal communities, in which small-sized (63-125 µm) benthic foraminifera play an important role:

1) The late Paleocene fauna was highly diverse and reached fairly high densities. It was mainly dominated (~50%) by two small-sized taxa: *Bulimina* cf. *thanetensis* and *Globocassidulina subglobosa*, but larger robust trochospiral taxa (e.g., *Cibicidoides* spp. and *Anomalainoides* spp.) were also common in this interval. The planktic community was composed of both deep and shallow-dwelling taxa. These communities are considered to reflect mesotrophic conditions with relatively high productivity and (fluctuating) low oxygen levels.

2) At the P/E boundary diversity and densities decreased strongly, coinciding with the global level of extinction of benthic foraminifera (BEE) and start of the Carbon Isotope Excursion (CIE). This marked the onset of the PETM and the seafloor remained nearly permanently anoxic and a-biotic during this early PETM interval. One level contained poorly preserved shallow-dwelling planktic foraminifera (dominant taxon: *Acarinina multicamerata* sp. nov.), an indication that surface waters most likely remained oxygenated during the early CIE/PETM.

3) During the middle PETM very low densities of a low-diverse/high-dominance benthic fauna appeared, indicating occasional re-oxygenation of the basin followed by short periods of repopulation of the benthic environment. Certain specialized taxa were able to thrive in the highly eutrophic conditions (e.g., *Anomalainoides aegyptiacus*, *Valvulineria* spp. and *Stainforthia* spp.). The planktic community started to diversify, although shallow-dwelling taxa remained dominant (*Acarinina*, *Morozovella*) indicating poor conditions for deep-dwelling taxa.

4) During the late to post-PETM long-term sustainable communities of foraminifera developed under mesotrophic conditions. The diversity and densities of the benthic and planktic faunas first increased strongly (DQ-bed 5), but in the post-PETM a slight
decrease is observed. Planktic faunas remained diverse with both deep and shallow-dwelling taxa. *Bulimina callahani* dominated the benthic assemblage, which is thought to be representative of low oxygen levels and/or high productivity.

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**Plate 1**

*Late Paleocene fauna*

a. *Angulogavelinella avnimelechi* (DBH -0.65)  
b. *Anomalinoideas affinis* (DBH -1.65)  
c. *Oridorsalis plumeriae* (DBH -1.07)  
d. *Alabamina midwayensis* (DBH -1.65)  
e. *Loxostomoides applinae* (DBH -0.45)  
f. *Osangularia plummerae* (DBH -2.68)  
g. *Osangularia plummerae* (DBH -3.18)  
h. *Sporobulimina eocaena* (DBH -1.07)  
i. *Bulimina midwayensis* (DBH -0.32)  
j. *Cibicidoides pseudoacutus* (DBH -1.65)  
k. *Cibicidoides pseudoacutus* (DBH -1.65)  
l. *Cibicidoides rigidus* (DBH -0.32)  
m. *Cibicidoides cf. hyphalus* (DBH -0.65)  
n. *Bulimina cf. thanetensis* (DBH -1.65)  
o. *Globocassidulina subglobosa* (DBH -1.65)  
p. *Pulsiphonina prima* (DBH 4.08)  
q. *Neopeponides lunatus* (DBH -0.32)  
r. *Spiroplectinella esnaensis/dentata* (DBH -0.82)  
s. *Dorothia* sp. (DBH -0.32)  
t. Undetermined agglutinated specimen (DBH -1.07)  
u. *Trochammina* sp. (DBH -1.07)  
v. *Bathysiphon* sp. (DBH -1.07)
Plate 2

Middle, late PETM and post-PETM fauna

a. *Anomalinoideas aegyptiacus*, apertural view (DBH 2.43)
b. *Anomalinoideas aegyptiacus* (DBH 2.68)
c. *Valvulineria scrobiculata*, dorsal view (DBH 1.93)
d. *Valvulineria scrobiculata*, umbilical view (DBH 1.93)
e. *Bulimina farafraensis* (DBH 2.68)
f. *Lenticulina* sp. (DBH 2.68)
g. *Stainforthia* sp. (DBH 4.58)
h. *Globocassidulina subglobosa* (DBH 4.58)
i. *Bulimina cf. thanetensis* (DBH 2.93)
j. *Bulimina callahani* (DBH 2.93)
k. *Valvalabamina depressa* (DBH -0.01)
l. *Valvalabamina depressa* (DBH -0.01)
m. *Valvalabamina planulata* (DBH 3.18)
n. *Valvalabamina planulata* (DBH 2.68)
o. *Anomalinoideas zitteli*, apertural view (DBH 2.68)
p. *Anomalinoideas zitteli* (DBH 1.93)
q. *Cibicidoides pharaonis/decoratus* (DBH 2.43)
r. *Cibicidoides pharaonis/decoratus* (DBH 2.68)
s. *Tappananina selmensis* (DBH 2.93)
t. *Uvigerina* sp. (DBH 2.93)
u. *Gaudryina* sp. (DBH 3.18)
v. *Turrilina brevispira* (DBH 3.18)
w. *Spiroloculina* sp. (DBH 3.18)
References


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CHAPTER VII

Synthesis
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Synthesis

1 Introduction

In the previous chapters, we discussed various aspects of paleoenvironmental changes along the southern Tethyan margin during the early Paleogene. We achieved to unravel long- and short-term environmental changes and important biotic turnovers across the Danian-Selandian transition and the Paleocene-Eocene thermal maximum. By combining quantitative foraminifera and organic-walled dinocyst data, we investigated the response of the marine system during the Paleocene, especially during climatic perturbations. A multi-proxy approach is preferable in these studies, in order to avoid misinterpretations and to extract a robust paleoenvironmental signal. This approach has been successfully applied in Tunisia, where we integrated sea-surface (organic-walled dinocysts) and sea-floor (benthic foraminifera) assemblages, in a case study at El Kef (NW Tunisia) covering a major part of the Paleocene (chapter II). In chapter III, organic dinocysts were combined with planktic foraminiferal assemblages in three localities in NW Tunisia, to shed light on the biotic changes across the Danian-Selandian transition. Other relevant aspects of this time interval were discussed in chapter IV, in which a paleobathymetric transect is investigated in the Middle East (in Egypt and Jordan). Planktic and benthic foraminiferal assemblages exhibit a transient turnover, in response to paleoenvironmental and paleoclimatic change. Along the same transect in the Middle East, planktic foraminiferal assemblages of the Paleocene/Eocene thermal maximum were investigated in chapter V. A detailed study across the PETM at Dababiya (Egypt) was presented in chapter VI, evaluating benthic and planktic foraminiferal assemblages.

In this final chapter, we portray an overview of the Danian-Selandian transition, comparing the main outcomes from Tunisia and the Middle East. Furthermore, this interval is compared with the PETM in the Middle East, keeping in mind that the studied parameters vary somewhat, primarily because of taphonomic differences.

2 Paleobathymetric reconstructions

Similar paleobathymetric settings were recognized in the Middle East and in Tunisia. In the Middle East, the studied localities were located on the continental margin, from middle neritic (75-100 m at Gebel Duwi) to outer neritic (150-200 m at Nile Valley localities) to upper bathyal (~200-300 in Jordan, 500 m at Wadi Nukhl). In Tunisia, paleodepths range from shallow outer neritic (100-150 m at Ain Settara) to deep outer neritic (<200 m at Elles and El Kef), shallower during certain periods in time (e.g. ~50 m: inner neritic-coastal at El Kef in Zone P4). Paleobathymetric evolution was reconstructed using marker benthic
foraminifera taxa, associated with the percentage of planktic foraminifera in the whole foraminiferal assemblages. For instance, high numbers of planktic foraminifera associated with deep-sea benthic taxa, the so-called Velasco-type fauna (Berggren and Aubert and, 1975) such as Gavelinella beccariiformis, Nuttallides truempyi and Angulogavelinella avimelechi suggest a deeper setting (deep outer neritic-bathyal), whereas low numbers of planktic foraminifera together with neritic Midway-type benthic faunas, such as Cibicidoides (C. pseudoacutus, C. rigidus), Anomalinoides praecacutus and Anomalinoides umboniferus are indicative of a neritic setting. In addition, organic dinocysts assemblages disclosed significant information on the distance from shore, refining the interpretation based on foraminifera. Whereas the presence, for instance, of the offshore dinocyst taxon Impagidinium during lower Paleocene Zones P2-P3a is in agreement with a deeper setting, increased abundance of peridinioid cysts and the Areoligera group are indicative of inner neritic-coastal conditions.

The studied basins were generally deep enough to enable a well-stratified water column, as evident in well-diversified planktic foraminiferal assemblages, which do not display significant variation related to differences in paleodepth. Only minor differences are recognized. For instance, higher numbers of planktic foraminifera Praemurica characterize the shallower locality in Egypt (Gebel Duwi), compared to the deeper localities, in accordance with the preference of this taxon for a shallower (and perhaps warmer) habitat. Striking is the higher abundance of the deep-dwelling Globanomalina in Tunisia, even at the shallowest locality, Ain Settara. Considering that the paleobathymetric range in these areas, based on the benthic foraminiferal assemblages is similar, this pattern cannot be related to depth. Instead, this pattern might be related to colder surface waters bathed Tunisian localities, as it is suggested also in heavier oxygen isotopic values in Tunisia. We speculate that the Tunisian localities were closer or better connected to the deep Tethys Ocean, whereas the others were situated on a much wider platform, most of them far away from the deep ocean.

3 Paleoproductivity reconstructions

Considering a combination of proxies, paleoproductivity variations have been reconstructed. Organic dinocysts are useful to estimate variations in primary productivity. In particular high numbers of peridinioid cysts compared to the gonyaulacoid cysts (a high P/G ratio) is a good estimation of increased productivity. Additionally, this ratio has been refined introducing the protoperidinioid/gonyaulacoid ratio (Pp/G) and evaluating the difference in estimating productivity change only considering extant cysts (i.e. Chapter II and III). For instance, a combination of high numbers of buliminids with increased numbers of protoperidinioid cysts more reliably indicates eutrophic conditions (i.e. at Kef in Zone P4).

Variations in planktic foraminiferal assemblages have also been evaluated, and this presented several difficulties related to the poorly known ecology of Paleocene foraminifera.
Whilst in the Modern Ocean, extant benthic foraminifera and organic dinocysts morphologically similar to fossil ones are found, enabling speculation on their ecology, this approach is not possible for the planktic foraminifera. In fact, there are no similar extant taxa and the complexity of trophic strategies typical of the modern taxa cannot be sufficiently evaluated in the fossil record. Therefore, a combination with other proxies is important for improving the knowledge on the ecology of planktic foraminifera (Chapter III to VI). The ecological characterizations that have been proposed thus far are not sufficient to be compatible with various paleoceanographic settings. For instance, peaks of symbiont-bearing surface dwellers taxa do not exclusively indicate oligotrophism. Instead, specific taxa (e.g. low trochospiral *Acarinina*) can be connected to increased productivity (Chapter IV, V and VI). Additionally, the planktic foraminiferal number (i.e. the number of planktic foraminifera per gram of sediment) should be evaluated as a basic parameter in paleoproductivity reconstructions using foraminifera, although it should be realized at the same time that dilution and dissolution can also interfere with this parameter.

Oligotypic benthic assemblages, dominated by specific foraminifera, such as buliminids, reflect the signal on the sea floor of increased primary productivity, usually in combination with low-oxygen conditions. A full qualitative evaluation is preferable, because it provides more detailed and robust interpretations (Chapter II, VI) but also a semi-quantitative survey can outline the main trends as demonstrated in Chapter IV.

4 The Danian-Selandian transition

Except for the PETM, unraveling short-term paleoenvironmental and paleoclimatic changes of the early Paleogene on a global scale has so far been hindered by limitations of the biostratigraphic and chronostratigraphic frameworks applied. A more robust and precise scheme would enable us to discern global events from merely local perturbations. This especially pertains the Danian-Selandian transition, for which there have been relatively few well calibrated integrated stratigraphic studies. Another complicating factor is the presence of stratigraphic discontinuities within the Danian-Selandian transition in many well studied areas in Europe, North America and - as appears in our study - also in North Africa. A side effect of all this is that a GSSP for the Danian/Selandian boundary has not been defined yet, and thus far, no specific criteria were connected to this transition, as, for instance, the CIE was a good correlation marker already before the definition of GSSP of Paleocene/Eocene boundary.

The Danian and Selandian Stages are chronostratigraphically equivalent to the lower Paleocene and the lower upper (“middle”) Paleocene, respectively. The boundary between these stages is defined in different ways, using various criteria. Berggren (1994) and Berggren et al. (1995) proposed to correlate the Danian/Selandian boundary with the P2/P3 zonal boundary, with an estimated age of 60.9 Ma, whereas Hardenbol et al. (1998)
estimated the age for sequence boundary Sel 1 in Western Europe at 60.7 Ma (within lower Subzone P3a).

Schmitz et al. (1998) proposed to define the GSSP of the Danian/Selandian boundary at Zumaya (northern Spain), positioning the base of the Selandian in a transitional interval including the lowest occurrence (LO) of calcareous nannofossil *Fasciculithus tympaniformis*. Instead, Steurbaut et al., (2000) proposed to locate this GSSP at Ain Settara (Tunisia).

In this work, we do not aim to solve this issue. However, in our view, the successive LOs of *Fasciculithus* spp. and *F. tympaniformis* represent suitable bio-events for correlation of low- and mid-latitude sections and it is between these bioevents that we find our indications for transient biotic and paleoenvironmental change.

### 4.1 The Danian-Selandian transition in the Middle East and Tunisia

In Egypt and Jordan, the Danian-Selandian transition is not marked by an overall lithological change. In fact, shaley marls dominate in most Paleocene successions in the region. However, this transition is marked by an organic-rich dark bed characterized by anomalous faunal assemblages. We named this event “Neo-duwi event”, as *Neoeponides duwi* is the dominant benthic taxon in this interval at every locality. Whereas planktic foraminiferal biostratigraphy is poorly constrained due to the problematic identification of *Igorina albeari*, the P3a/b zonal marker, calcareous nannofossils enable a precise limitation of this event. In fact, this transient episode occurred near the top of Zone NP4 between the respective LOs of *Fasciculithus* spp. and *F. tympaniformis*, which corresponds to the base of Subzone P3b.

Following Berggren et al. (1995), these bio-events occurred at 59.9 Ma and at 59.7 Ma, respectively, suggesting that the “Neo-duwi event” lasted for less than 200 ky. Although in Tunisia, such a distinct marker bed and associated anomalous faunal assemblages are not present, some similarities can still be traced. A long-term environmental change is described from open marine oligotrophic conditions toward eutrophic neritic settings in the upper Paleocene. This change in paleobathymetry and paleoproductivity started at the base of Subzone P3b, about 1m above the lowest occurrence of *Fasciculithus* spp., and coincided with the lowest occurrence of *Apectodinium*.

Differences between Tunisia and the Middle East are mainly evidenced in the high sediments thickness between the LOs of *Fasciculithus* spp. and of *F. tympaniformis* in Tunisia, indicating much higher sedimentation rates in Tunisia as compared to the Middle East. We estimated a sedimentation rate varying between 70 m/Ma and ~150 m/Ma in Tunisia (at Elles and at Ain Settara, respectively) and between ~ 27 m/Ma and 35 m/Ma in the Middle East (at Shaubak and at Awaina, respectively). The high sedimentation rate in the Tunisian localities suggests high subsidence rates accommodating for the high clay input from land filling the basin (Tunisian Trough). The studied parts of the basins in Egypt and Jordan received less input and experienced much lower subsidence rates.
Considering the differences in basic basin dynamics between these areas, it is striking that the environmental changes observed occurred at the same stratigraphic level, suggesting that these local perturbations were probably part of a more regional environmental reorganization, and we suggest that they represent the local expression of a more general, paleoclimatic/paleoceanographic perturbation.

4.2 Comparison with Zumaya
Not only the southern Tethys seemed to have been affected by paleoenvironmental changes during the middle Paleocene. Biotic and isotopic variations characterized northern Spanish sections as well, for instance, Zumaya. At this locality, the base of the Selandian corresponds to 3.4 m of red marls forming a transitional interval from the red marl-limestone couplets below to the grey marls above. At the base of the red marls, the calcareous nannofossil *Neochiastozygus perfectus* occurs, and at 75 cm above the base, the LO of *Fasciculithus tympaniformis* (base of Zone NP5) is recorded. In the Middle East, the interval between the LO of *N. perfectus* and the LO of *F. tympaniformis* is ~14.5 m at Shaubak (Jordan) at least 8 m at Aweina (Egypt). Since a much higher sedimentation rate in these sections than in Zumaya is perhaps unlikely, considering the much greater overall thickness of Zumaya succession, we cannot exclude the possibility that a hiatus or condensed interval occurred at the lithological change in Zumaya. Alternatively, diachronism of the LO of *N. perfectus* might be more likely. This remains to be scrutinized.

Also in the Zumaya section, in the *Morozovella angulata* zone (= Subzone P3a), a peak occurrence of *Morozovella* was interpreted as a brief interval of increasing surface water temperature (Arenillas and Molina, 1995). At the base of the *M. crosswicksensis* zone (corresponding to upper P3a - lower P3b), the main lithological change is combined with a level of partial dissolution, sea-level rise and an increased cold/warm ratio, evidenced in the decrease of surface dwelling planktic foraminifera (Arenillas and Molina, 1996). Schmitz et al. (1998) identified a shift of the δ¹³C of ~1‰ at the base of the Selandian. This shift started at the lowest occurrence of *N. perfectus* (upper Zone NP4) and continued in Zone NP5. In the Middle East sections, diagenetic overprint led to variable δ¹³C values, so there is no good evidence for a similar shift there, but it cannot be excluded.

Diachronism of events at Zumaya and in the Middle East might to some extent be related to the different applications of standard biozonations. Particularly the LO of *Igorina albeari* (P3a/b zonal marker) is problematic. However, the nannofossil bio-events suggest a similar interval between the isotopic shift at Zumaya and the paleoenvironmental change in the southern Tethys, especially in the Middle East around 59.8 Ma.
5 Paleocene/Eocene thermal maximum

The GSSP of the Paleocene/Eocene boundary has been recently defined at Dababiya, Egypt (Ouda and Aubry, 2003). The base of the Ypresian coincides with the onset of the Carbon Isotopic Excursion (CIE), with the base of the PETM and with the global level of extinction of benthic foraminifera (BEE).

The impact of this hyperthermal event has been evaluated on foraminiferal assemblages in the Middle East (chapter V, VI).

The late Paleocene benthic and planktic foraminiferal assemblages were highly diversified, reflecting mesotrophic conditions with relatively high productivity and (fluctuating) low oxygen levels. At the P/E boundary, diversity strongly decreased. During the early PETM the seafloor remained nearly permanently anoxic and a-biotic, and only one level is dominated by poorly preserved shallow-dwelling planktic foraminifera *Acarinina* (dominant taxon: *Acarinina multicamerata*), suggesting highly stressed environmental conditions. After this extreme time, oligotaxic benthic fauna (e.g., *Anomalinoildes aegyptiacus, Valvulineria* spp. and *Stainforthia* spp.) appeared, indicating occasional re-oxygenation of the basin followed by short periods of repopulation of the benthic environment. The planktic community started to diversify, although shallow-dwelling taxa (*Acarinina* and *Morozovella*) remained dominant. In the late post-PETM phase, the diversity and densities of foraminiferal assemblages increased, suggesting ameliorating of environmental conditions and the gradual return of pre-PETM conditions.

5.1 Was the Neo-duwi event a precursor of the Paleocene-Eocene thermal maximum?

As already mentioned in previous sections, the comparison between events across the Danian-Selandian transition and the Paleocene/Eocene boundary can only be discussed on the basis of our data from the Middle East.

A dark organic rich bed, characterized by anomalous foraminiferal assemblages is the most distinctive feature of these events. At the PETM, stress-tolerant *Acarinina* dominated the planktic assemblages (Chapter V), and opportunistic middle neritic *Anomalinoildes aegyptiacus* assemblages invaded the sea floor (Speijer et al., 2000; Chapter VI) in response to eutrophic conditions and poor and variable oxygenation. Similarly, at the “Neo-duwi event”, we also observe the flourishing of *Acarinina* in the Nile Valley sections, presumably in response to increased runoff and nutrient supply. At the same time, a bloom of small-sized *Morozovella* and *Prinsius martini* indicated an upwelling regime in the eastern part of the basin. However, the *Neoeponides duwi* assemblage dominated everywhere. This taxon exhibits a similar opportunistic strategy towards dysoxic to anoxic conditions as the *Anomalinoildes aegyptiacus* assemblage during the PETM.
Additionally, both event-beds are thought to have been deposited during rapid sea-level rise after a sea level low-stand (Speijer 2003). In particular, the deposition of the “Neo-duwi event” is associated with the sequence boundary Sel 1 (Hardenbol et al., 1998).

However, the distinct negative carbon isotopic excursion, which characterized the PETM, is certainly not found at the Danian-Selandian transition. The reason for this may be that there was no true isotopic excursion, or it is simply not visible because any possible variations are compromised by diagenetic overprinting. Since several features of the “Neo-duwi event” are strongly reminiscent of those associated with the PETM, we believe that these similarities point at least to locally analogous operative processes.

In the deep ocean, various hyperthermals have been suggested before and after the PETM (Thomas and Zachos, 2000; Thomas et al., 2000; Bralower et al., 2002) but are still awaiting confirmation by more detailed and extensive studies. Some of the suggested hyperthermals (i.e. in planktic foraminifera Zones P3a and P4) are associated with anomalous foraminiferal assemblages (Thomas and Zachos, 2000; Bralower et al., 2002, Petrizzo, 2005). At present, there is no evidence of a hyperthermal event at 59.8 Ma, as we estimated “Neo-duwi event”, recorded in the open ocean.

On the other hand, our studies provided unexpected difficulties in the application of standard zonation schemes for the middle Paleocene in the whole area and thus also the usage of these schemes for this interval elsewhere may be compromised by taxonomic problems, diachronism and unrecognized hiatuses.

6 Perspectives

Our research is part of a broader research effort, aiming to understand early Paleogene geobiosphere changes. Beyond the well-known PETM, recent Ocean Drilling cruises and the research reported here portray significant environmental changes related to the occurrence of several short-term climatic events during the middle-upper Paleocene and in the lower Eocene. Thus far, only fragmentary outcomes on these climatic changes are displayed.

Two main issues are required in further research. First, accurate studies on the Tethyan areas focusing on more detailed datasets are essential, in order to enable the reconstruction of climatic change on regional scale. To achieve this point, suitable outcrops, in which diagenetic processes and weathering have altered the signal to a lesser extent, are important for a multi-proxy approach.

Second, the comparison with the oceanic system is the next important step to be enhanced. We believe that mismatches between climatic events in continental margin and oceanic records may have resulted from poor age calibrations. Indeed, some key bio-events (nannofossils and foraminifera) were probably not synchronous between the Tethys and the global ocean and the age model of bio-events needs further refinement. Whilst sediments
from the deep ocean are characterized by orbitally controlled cyclicity of measurable and visible parameters, allowing precise correlation and age calibration, this approach is more difficult in Tethyan outcrops. Especially, suitable localities in the generally diagenetically altered monotonous marls of the marginal Southern Tethys are hard to find.

Finally, we demonstrate that the ecology of Paleocene planktic foraminifera is still poorly known and hence not adequate to distinguish between different paleoceanographic scenarios. In particular, trophic regimes and symbiotic partnerships require further exploration. Recent investigation on isotopic signal on certain species demonstrated that these taxa were ecological more distinguished than prior suggested. This seems the right direction into concentrate future researches to discriminate diversity in the ecological signals.

References


APPENDIX
**Tunisia**

**Ellés 35°56'66“ N 9°05'02“ E**

*Above:* overview of the lower to upper Paleocene El Haria Formation and the overlying Ypresian Metlaoui Formation. The white rectangular indicates the closer view of the picture below.

*Below:* closer view of white rectangular of the picture above showing the middle Paleocene and the lithological change toward more shaley marls.
Tunisia

*Ain Settara* 35°47'83" N 8°26'60" E

**Above**: overview of the outcrop. View of the Paleocene of El Haria Formation and the Ypresian of Metlaoui Formation. The studied section is indicated by the vertical line.

**Left**: studied section.
Jordan

Shaubak (Wadi Bustani): 30°35'07” N, 35°35'10” E

Above: overview of the whole outcrop. Grey Paleocene marls of Muwaqqar Formation are overlain by the chalky limestone of Umm Rijam Formation.

Left: close-up of the dark-shaly bed partially laminated at the Danian-Selandian transition bed (“Neo-duwi event”).
Above: overview of Gebel Qurtayssiat. Paleocene Muwaqqar Formation overlain by Ypresian Umm Rijam Formation.

Left: close-up of the dark-shaley bed at the Paleocene/Eocene thermal maximum
Egypt

Dababiya 25°30’ 00”N, 32°31’52“ E

a: overview of the outcrop; the arrow indicates the position of the P/E GSSP, which is located behind the nose.
b: Location of the GSSP (section DBH).
c: close-up of the GSSP with the golden spike.