

# THE PROGRESSION OF ENVIRONMENTAL CHANGES DURING THE ONSET OF THE PALEOGENE-EOCENE THERMAL MAXIMUM (NEW JERSEY COASTAL PLAIN)

Peter STASSEN<sup>1\*)</sup>, Ellen THOMAS<sup>2)3)</sup> & Robert P. SPEIJER<sup>1)</sup>

## KEYWORDS

sedimentation rate  
Foraminifera  
Wilson Lake  
New Jersey  
low oxygen  
Bass River  
PETM  
onset

<sup>1)</sup> Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, B-3001, Leuven, Belgium;

<sup>2)</sup> Department of Geology and Geophysics, Yale University, Whitney Avenue 210, New Haven, Connecticut 06520-8109, USA;

<sup>3)</sup> Earth and Environmental Sciences, Wesleyan University, Exley Science Center 459, Middletown, Connecticut 06459, USA;

<sup>\*</sup> Corresponding author, peter.stassen@ees.kuleuven.be

## ABSTRACT

Chemostratigraphic and biostratigraphic studies of Paleocene-Eocene boundary sequences in the New Jersey Coastal Plain reveal that the Paleocene-Eocene thermal maximum (PETM) corresponds to a basin-wide, thick clay unit. Benthic foraminifera have been studied at low resolution, but we present the first high-resolution benthic foraminiferal data and paleoecologic interpretations of the more landward Wilson Lake and more seaward Bass River drill sites. Graphic correlation allows refinement of the site-to-site correlation, providing insight in the succession and timing of environmental changes associated with the onset of the PETM. Uppermost Paleocene glauconitic sandy strata were deposited at very low sedimentation rates (Bass River ~ 1 cm/kyr and Wilson Lake ~ 0.1 cm/kyr). Deposition occurred in stable, well-oxygenated deep middle neritic (Wilson Lake,) to outer neritic environments (Bass River). No changes in benthic assemblages are associated with the start of the *Apectodinium* acme or the proposed pre-PETM sea surface temperature rise. The onset of the PETM, as characterized by the base of the carbon isotope excursion (CIE), is at the transition from glauconitic sands to silty clay, coinciding with a major benthic foraminiferal change towards a more outer neritic assemblage consisting of opportunistic taxa. The onset of the PETM is represented in a transitional fauna present in the updip Wilson Lake site (sedimentation rate ~ 16.9 cm/kyr), whereas the more downdip section (Bass River) contains a relatively condensed interval (sedimentation rate ~ 2.8 cm/kyr). In the record from the expanded Wilson Lake sequence, the start of a major sea level rise coincided with the onset of the CIE and preceded the establishment of the dysoxic eutrophic conditions in the earliest PETM as indicated by the low-diversity, opportunist dominated benthic foraminiferal assemblages. This low-diverse assemblage probably reflects the establishment of persistent stratification and subsequent dysoxic sea floor conditions. Increasing benthic diversity indicates a steady environmental recovery later in the PETM, during which seasonal dysoxic eutrophic conditions still created periodic stress for the benthic biota. Site-to-site correlation indicates an increase in sedimentation rates for this interval (Wilson Lake ~ ≥21.4 cm/kyr and Bass River ~ ≥10.0 cm/kyr), in association with high influxes of low-salinity tolerant dinoflagellates. Overall, benthic communities indicate no environmental changes prior to the PETM and the rapid development of a stratified water column during the PETM, leading to permanent dysoxic bottom water conditions, followed by a gradual decline in stratification and only seasonal dysoxia.

## 1. INTRODUCTION

The early Paleogene world was a greenhouse world with high atmospheric CO<sub>2</sub> levels and high mean global temperatures (e.g. Thomas et al., 2006), yet this greenhouse world was climatically dynamic and characterized by relatively short key intervals of rapid global warming, called hyperthermals. The Paleocene-Eocene thermal maximum (PETM) is the most pronounced and best known hyperthermal (Zachos et al., 2008). The environmental and biotic impact of the PETM has been studied worldwide by using various proxies (e.g. stable isoto-

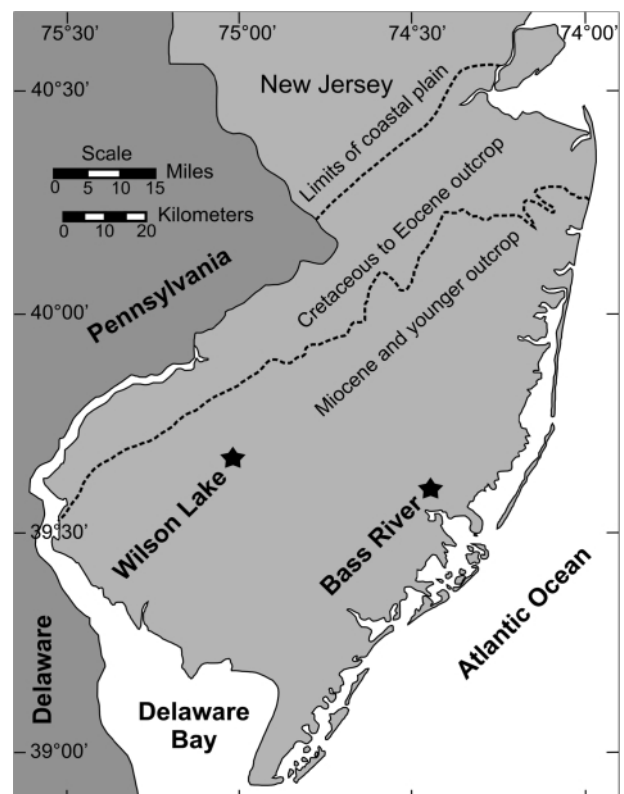
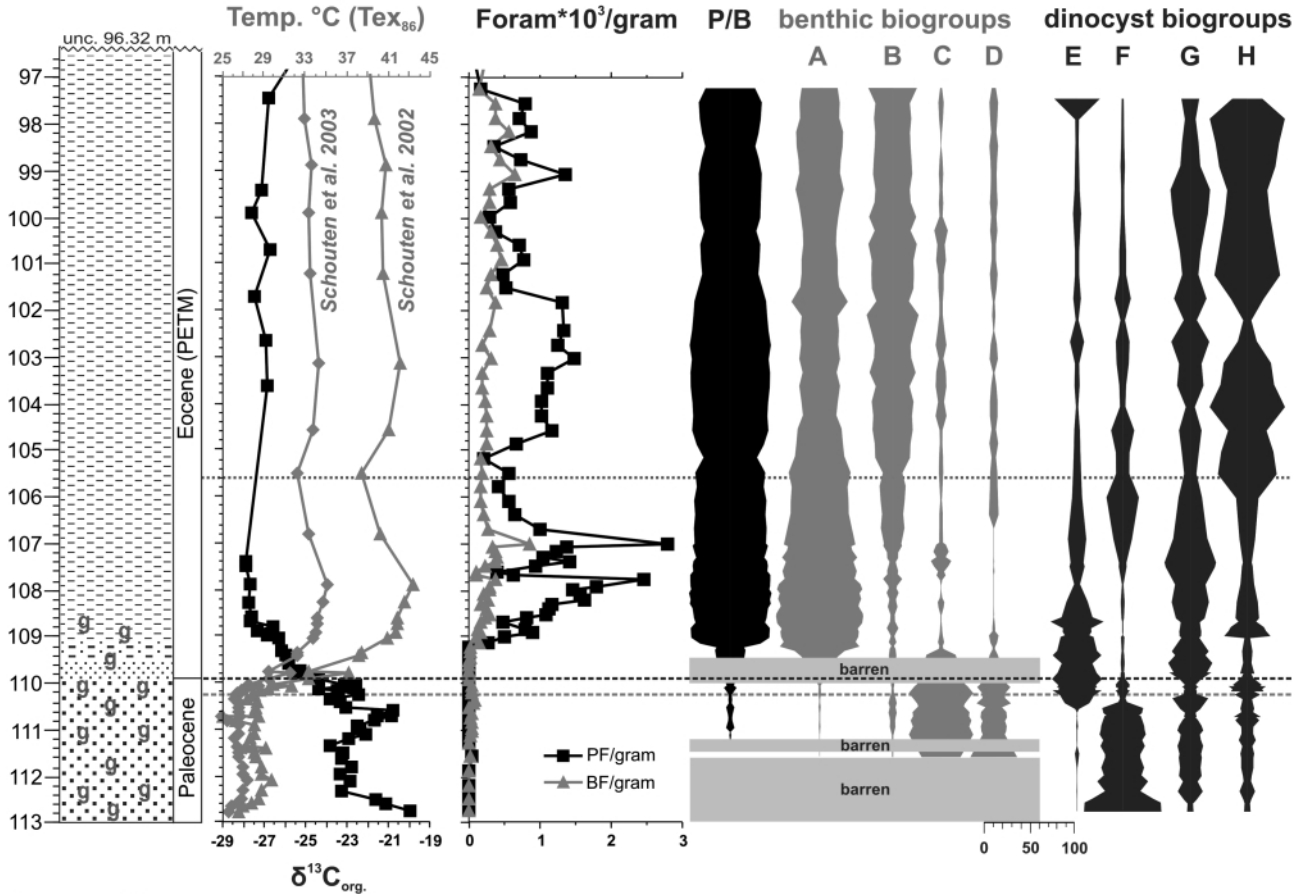


FIGURE 1: Location of the Wilson Lake and Bass River core sites (modified after Miller, 1997).

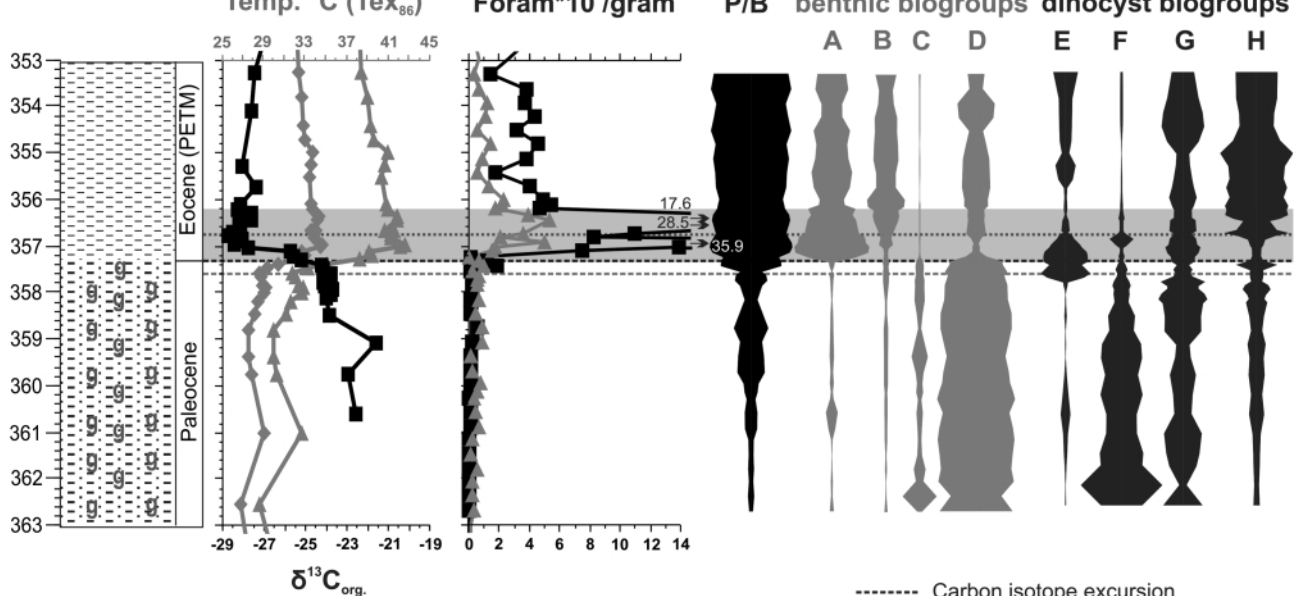
pes, microfossils, macrofossils ...; see overviews in Sluijs et al., 2007a; McInerney and Wing, 2011 and Speijer et al., 2012) providing insight into the overall impact of rapid global war-

ming on the global biosphere. In addition, detailed paleoenvironmental reconstructions of expanded Paleocene-Eocene boundary sequences will allow further understanding of the

### Wilson Lake



### Bass River



- fine to medium sand
- very fine sand/silt/clay
- clay
- fine sand and silt
- silty clay/clay
- g glauconite

- Carbon isotope excursion
- surface ocean warming
- ..... lowest occurrence of *T. bramlettei*

**FIGURE 2:** Geochemical (dinocyst δ<sup>13</sup>C and TEX<sub>86</sub> records, Sluijs et al., 2007b) and biotic records across the Paleocene-Eocene boundary in the New Jersey Coastal Plain (Wilson Lake and Bass River). TEX<sub>86</sub> calibrations are based on Schouten et al. (2002; 2003). See table 1 for explanation of the biogroups.

sequence of feedback mechanisms and specific biotic responses to enhanced greenhouse effects.

The New Jersey Coastal Plain contains some of the most expanded marine sedimentary records of the Paleocene-Eocene boundary in North America (Gibson et al., 1993). The lithology consists predominantly of bioturbated glauconitic sandy to clayey sediments deposited in a sediment-starved siliciclastic shelf environment (ramp type), associated with high sea level (Browning et al., 2008). Olsson and Wise (1987) described an interval with unusual lithology (clayey strata) and small-sized poorly diverse benthic foraminiferal assemblages near the P-E boundary. Stable carbon isotope measurements allowed the recognition of the CIE within this clayey interval at Wilson Lake and Bass River (Figs. 1 and 2), indicating that the PETM interval is captured in the New Jersey Coastal Plain. These isotope records allowed a detailed positioning of the CIE onset (Wilson Lake ~ 110.0-109.9 m and Bass River 357.3 m; Cramer et al., 1999; Zachos et al., 2006; Sluijs et al., 2007b; John et al., 2008), yet the exact duration of the PETM is a matter of debate as the top of the PETM interval is truncated by unconformities.

In the New Jersey Coastal Plain, surface water environmental and temperature changes preceded the onset of the CIE by several thousand years (Sluijs et al., 2007b). An *Apectodinium* dinocysts acme started before the initiation of surface warming as shown in the TEX<sub>86</sub> record, and both phenomena preceded the main perturbation of the carbon cycle (Sluijs et al., 2007b). Dinocyst distribution, grain size fractions and organic biomarkers suggest an increased distance to the coastline during the latest Paleocene and the inferred sea-level rise started 20 to 200 kyr before the onset of the CIE (Sluijs et al.,

2008). Nannoplankton data indicate an increased nutrient availability on the New Jersey Coastal Plain shelf during the PETM (Gibbs et al., 2006b). Only low-resolution benthic foraminiferal studies are available (Gibson et al., 1993; Harris et al., 2010) and these findings support the hypothesis that sea level rose across the Paleocene-Eocene boundary and that oxygen minimum zones become established due to high productivity.

These high-resolution isotope and biotic studies on the sedimentary sequences of the New Jersey Coastal Plain provided evidence to unravel the progression of environmental changes during the onset of the PETM, but did not include detailed evidence based on sea floor biota. We present high-resolution benthic foraminiferal records of the Wilson Lake and Bass River sites, which enable us to reconstruct a more detailed view of paleoenvironmental evolution of this siliciclastic shelf during the onset of the PETM.

## 2. MATERIAL AND METHODS

Samples were obtained from the Wilson Lake and Bass River drill sites on the New Jersey Coastal Plain (Fig. 1). Microfossil residues were obtained following conventional washing procedures (e.g. Ernst et al., 2006) and compositional foraminiferal data were obtained from the >63 µm fraction. Foraminiferal biogroups were established by cluster analysis and only the most common components are discussed here. Paleoenvironmental preferences of these benthic foraminiferal biogroups are summarized in table 1 (based on Olsson and Wise, 1987; Gibson et al., 1993; Browning et al., 1997; Liu et al., 1997; Ernst et al., 2006). Graphic correlation is based on distinct biotic events in the dinocyst (Sluijs and Brinkhuis, 2009) and foraminiferal records (Table 2). An unconformity is apparent at

bioindicator	biogroup	species	paleoecologic signal
high Planktic-Benthic ratio		not applicable	open marine conditions and/or poor bottom water oxygenation
benthic foraminifera	A	<i>Tappanina selmensis</i> <i>Anomalinoidea acutus</i> <i>Pulsiphonina prima</i>	long-term stratification with dysoxic bottom conditions; outer neritic marine conditions
	B	<i>Spiroplectinella laevis</i> <i>Pseudouvierina wilcoxensis</i>	seasonal less stressed dysoxic bottom conditions; outer neritic marine conditions
	C	<i>Bulimina virginiana</i> <i>Cibicidoides alleni</i> <i>Cibicidoides howelli</i>	oxic middle neritic marine conditions
	D	<i>Paralabamina lunata</i> <i>Gavelinella beccariiformis</i> <i>Bulimina homerstowensis</i>	oxic outer neritic marine conditions
dinocysts	E	<i>Apectodinium</i> spp.	heterotrophic lifestyle
	F	<i>Areoligera</i> complex	high energetic shallow shelf environments
	G	<i>Spiniferites</i> complex	open marine conditions
	H	<i>Senegalinium</i> complex <i>Cordosphaeridium fibrospinosum</i> cpx. <i>Membranosphaera</i> spp.	low-salinity tolerant group

TABLE 1: Summary of the known paleoecologic preferences of selected benthic foraminiferal and dinoflagellate (Sluijs and Brinkhuis, 2009) biogroups.

96.32 m in the Wilson Lake core (Gibbs et al., 2006b). An upper Paleocene sequence boundary is proposed at 359.0-359.1 m in the Bass River core (Sluijs et al., 2008; Harris et al., 2010). The applied age model is based on calcareous nannofossils (lowest occurrence of *Tribrachiatus bramlettei* ~ ±26 kyr after the onset of the CIE, Agnini et al., 2007), duration of the interval with sustained minimum δ<sup>13</sup>C values (CIE “core” ~ 71.25 kyr, Röhl et al., 2007) and uppermost Paleocene Bass River sedimentation rates (~ 1cm/kyr, Sluijs et al., 2008).

### 3. RESULTS

#### 3.1 SITE-TO-SITE CORRELATION

Changes in relative abundance in the dinocyst and foramini-

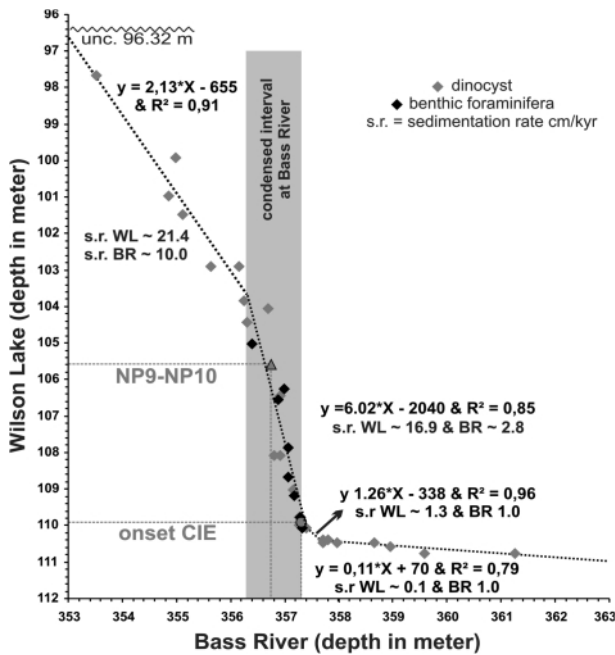
feral records allow a detailed correlation between the two sites (Figs. 2 and 3), in which a 5.8 m thick uppermost Paleocene interval at Bass River corresponds to a 1 m thick interval at Wilson Lake. Yet the onset of the *Apectodinium* acme and temperature rise at Wilson Lake are clearly distinct from the base of the CIE (109.9 m) by respectively 50 and 25 cm, which corresponds roughly to the same position at Bass River (respectively 40 and 25 cm). Therefore the Paleocene correlation is based on two trend lines ranging from base to the onset of the *Apectodinium* acme and from this acme to the onset of the CIE, implying higher sediment accumulation rates at Wilson Lake during the *Apectodinium* acme.

Extremely high foraminiferal numbers in the basal part of the CIE at Bass River (in excess of biologically reasonable accu-

Bass River mbs	Wilson Lake mbs	Description	Event	Remarks
353.52	97.67	<i>Apectodinium</i> abundance increase	dinocyst	
354.85	100.97	<i>Senegalinium</i> cpx. abundance increase	dinocyst	
354.99	99.93	peak abundance of <i>Membranosphaera</i> spp.	dinocyst	tentative correlation
355.12	101.48	<i>Apectodinium</i> abundance decrease	dinocyst	tentative correlation
355.63	102.91	<i>Apectodinium</i> abundance increase	dinocyst	tentative correlation
356.16	102.91	<i>Cordosphaeridium fibrospinosum</i> cpx. abundance decrease	dinocyst	
356.25	103.85	<i>Senegalinium</i> cpx. abundance increase	dinocyst	tentative correlation
356.3	104.43	peak abundance of <i>Cordosphaeridium fibrospinosum</i> cpx.	dinocyst	tentative correlation
356.39	105.03	second <i>Pseudouvirgerina wilcoxensis</i> abundance increase	benthic foram.	tentative correlation
356.59	104.42	termination of <i>Tappanina selmensis</i> acme	benthic foram.	tentative correlation
356.69	104.07	peak abundance of <i>Membranosphaera</i> spp.	dinocyst	tentative correlation
<b>356.74</b>	<b>105.6</b>	<b>lowest occurrence <i>Tribrachiatus bramlettei</i></b>	nannoplankton	
356.8	108.09	onset short-lived acme of Goniodomid taxa	dinocyst	
356.88	106.56	common occurrence of <i>Paralabamina lunata</i> (reoccurrence)	benthic foram.	
356.91	106.45	<i>Cordosphaeridium fibrospinosum</i> cpx. abundance increase	dinocyst	
356.91	108.09	termination of <i>Apectodinium</i> acme	dinocyst	
356.98	106.25	<i>Eouvigerina whitei</i> ? abundance increase	benthic foram.	
357.07	107.86	<i>Pseudouvirgerina wilcoxensis</i> abundance increase	benthic foram.	tentative correlation
357.07	108.66	<i>Pulsiphonina prima</i> acme	benthic foram.	tentative correlation
357.16	109.01	<i>Florentinia reichartii</i> abundance increase	dinocyst	tentative correlation
357.18	109.19	onset of <i>Tappanina selmensis</i> acme	benthic foram.	
357.26	109.99	<i>Hystrichosphaeridium</i> spp. abundance increase	dinocyst	tentative correlation
357.26	109.77	<i>Mebranosphaera</i> spp. abundance decrease	dinocyst	tentative correlation
357.29	109.76	onset <i>Anomalinoides acutus</i> acme	benthic foram.	
357.29	109.76	<i>Pulsiphonina prima</i> abundance increase	benthic foram.	
<b>357.3</b>	<b>109.9</b>	<b>onset carbon isotope excursion</b>	isotope	
357.33	110.06	highest occurrence of <i>Gavelinella beccariiformis</i>	benthic foram.	excluding reworking
357.39	110.08	peak abundance of <i>Membranosphaera</i> spp.	dinocyst	tentative correlation
357.71	110.38	<i>Membranosphaera</i> spp. abundance increase	dinocyst	
357.71	110.47	onset of <i>Apectodinium</i> acme	dinocyst	
357.8	110.38	<i>Cordosphaeridium fibrospinosum</i> cpx. abundance decrease	dinocyst	
357.97	110.47	<i>Hystrichosphaeridium</i> spp. abundance increase	dinocyst	tentative correlation
358.96	110.47	<i>Areoligera</i> cpx. abundance decrease	dinocyst	
358.96	110.57	Goniodomid taxa abundance increase	dinocyst	
359.59	110.77	Goniodomid taxa abundance decrease	dinocyst	
361.26	110.77	<i>Cordosphaeridium fibrospinosum</i> cpx. abundance increase	dinocyst	

**TABLE 2:** Biotic and isotope events recognized at Wilson Lake and Bass River (dinocyst events after Sluijs and Brinkhuis, 2009; nannoplankton after Gibbs et al., 2006a).





**FIGURE 3:** Graphic correlation based on significant benthic foraminiferal, dinocyst (Sluijs and Brinkhuis, 2009), nannoplankton (Gibbs et al., 2006a) and isotope events (Sluijs et al., 2007b). The depth-depth plot indicates relative sedimentation rates between Wilson Lake and Bass River and visualizes the extent of the condensed interval at Bass River. Sedimentation rates (s.r.) are calculated based on isotope and nannoplankton correlations.

mulation rates of foraminiferal tests) suggest that the lowermost interval of the CIE is more condensed than at Wilson Lake (Fig. 2), in agreement with the dinocyst-based correlation between the two sites (Sluijs and Brinkhuis, 2009). Condensation is also indicated by the position of the NP9b-NP10 zonal boundary, which is positioned immediately above the onset of the CIE at Bass River, whereas a much longer NP9b interval is present at Wilson Lake (Gibbs et al., 2006a). The two proposed correlation lines for the PETM interval correspond to the subdivision of a condensed lower part and more expanded upper part at Bass River (Fig. 3). According to this correlation, the uppermost PETM level below the Wilson Lake unconformity at 96.32 m correlates with the 352.85 m level at Bass River, which is different from an earlier proposal of correlation to 354.34 meter (Sluijs and Brinkhuis, 2009). Both proposed correlations indicate that the PETM interval continues at Bass River, whereas the Wilson Lake interval is limited to the CIE "core" (Stassen et al., 2009).

### 3.2 FORAMINIFERAL TURNOVER

Benthic foraminiferal biogroups (A to D in Fig. 2) do not show significant biotic events within the uppermost Paleocene interval. The main difference between the Wilson Lake and Bass River sites is the different proportion of middle and outer neritic foraminifera (Fig. 2 and Table 1). The higher proportion of the middle neritic biogroup (C) at Wilson Lake is in agreement with its shallower, more landward setting. The dominance of a middle neritic biogroup (*Bulimina virginiana* assemblage) and the persistence of outer neritic components at Wilson Lake in-

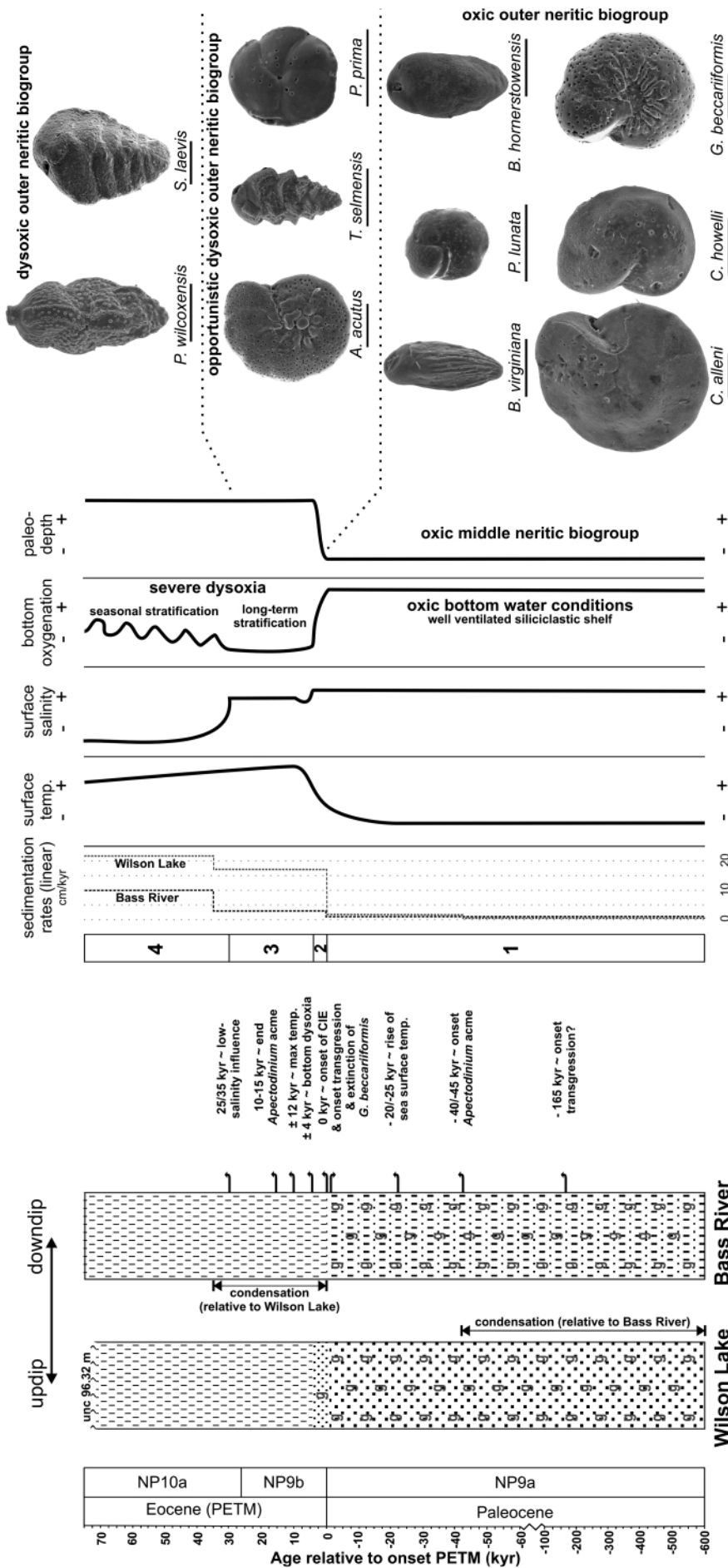
dicate a deep middle neritic paleodepth (90-100 m), whereas the Bass River assemblage is mainly composed of the outer neritic biogroup (D, *Gavelinella beccariiformis* assemblage), indicating a greater water depth of ~150 m.

At the onset of the CIE, these Paleocene biogroups were rapidly replaced by an opportunistic biogroup (A), mainly composed of *Tappanina selmensis*, *Anomalinoides acutus* and *Pulsiphonina prima*. The planktic-benthic ratio (P/B) rapidly increased at the onset of the CIE, but the low abundance of planktic foraminifera within the uppermost Paleocene glauconitic sands may have been taphonomically rather than environmentally controlled (e.g. physical destruction by abrasion in sandy sediments or dissolution in slowly accumulating sediments). At both sites, the highest occurrence of *Gavelinella beccariiformis* is just below the onset of the CIE. According to the proposed correlation, the onset of the PETM is most expanded at Wilson Lake and therefore best suited to investigate the sequence of PETM related biotic events. The basal PETM interval at Wilson Lake shows a gradual lithologic transition compared to Bass River, while the biotic turnover is characterized by a gradually increasing P-B ratio and increasing dominance of the opportunistic biogroup A (Fig. 2). Benthic assemblages are more diverse from 107 m upward at Wilson Lake, as reflected in the decrease in abundance of the opportunistic biogroup (A) and higher proportions of the outer neritic *Pseudouvirgerina wilcoxensis* and *Spiroplectinella laevis* biogroup (B). Both biogroups become equally dominant from 105.5 m upward, within the interval with higher proportions of low-salinity tolerant dinoflagellates (biogroup H in Fig. 2; Sluijs and Brinkhuis, 2009). Similar patterns are recorded at Bass River.

### 3.3 BIOTURBATION AND COMPLETENESS OF THE RECORD

Disruption by mixing (bioturbation or reworking) should not influence paleoecologic interpretations unless there are significant biotic changes in the assemblages over a short time span. This is the case at the onset of the PETM, where Paleocene biogroups (C and D) were rapidly replaced by PETM biogroups (A and B). Sluijs et al. (2007b) stated that the onset of the *Apectodinium* acme below the CIE is not an artifact of bioturbation. Our observations on benthic foraminifera confirm this assumption, as species belonging to the characteristic PETM biogroups are only rarely encountered below the CIE. The more gradual biotic turnover at Wilson Lake is likewise not an artifact of sediment mixing. Isotope measurements on *Cibicidoides allenii* and *Anomalinoides acutus* specimens, belonging respectively to the middle neritic Paleocene biogroup (C) and the PETM opportunistic biogroup (A), reveal that both species have typical CIE values (Stassen et al., 2009).

In contrast, reworking occurred at the PETM lithologic transition at Bass River (357.26–357.23 m). *Cibicidoides* spp. and *Gavelinella beccariiformis* specimens with relatively high (pre-CIE) values in both carbon and oxygen isotopes are reported above the onset of the CIE (Cramer et al., 1999). As *Cibicidoides* spe-



cimens are very rare in the lower part of the CIE and *G. beccariformis* is considered to have become extinct at this level, it is plausible that these specimens were bioturbated upwards, or transported through erosion of uppermost Paleocene sediments nearby. PETM biogroup species (e.g. *Anomalinoidea acutus*) have typical CIE values (Cramer et al., 1999).

Based on the foraminiferal isotope record, the benthic fauna within the lithologic transition at Bass River is most probably composed of a mixture of Paleocene and earliest Eocene specimens. This mixed interval is relatively thin, and its presence does not affect the dinocyst distribution (*Apectodinium acme*) or TEX<sub>86</sub> interpretation. Yet, foraminiferal numbers within the basal PETM interval at Bass River fluctuate significantly with several accumulation levels. Therefore, the presence of one or several small discontinuities within this relatively condensed interval cannot be excluded and these small uncertainties may hamper detailed correlation of the onset between the two sites (John et al., 2008).

### 3.4 SEDIMENTATION RATES

Uppermost Paleocene sedimentation rates at Bass River were in the order of 1 cm/kyr (Sluijs et al., 2008). Based on our correlation lines, sedimentation rates at Wilson Lake were around 0.1 cm/kyr in the lowermost part of the record (Fig. 3). The assumption of a different trend line between the onset of the *Apectodinium* acme and the CIE implies an increase in sedimentation rates prior to the PETM at Wilson Lake (1.3 cm/kyr), assuming constant Paleocene sedimentation rates at Bass River. The onset of the *Apectodinium*

**FIGURE 4:** Sequence of environmental changes during the onset of the PETM (1-4 refer to the sequence of sea floor environments, scale bar represents 100 μm). Note the scale break which enables an enlargement of the PETM interval).

acme and the initial temperature rise preceded the onset of the CIE by respectively 4-5 and 1-2 kyr (Sluijs et al., 2007b), with this timing based on extrapolation of PETM sedimentation rates towards the interval underlying the PETM. This assumption of constant sedimentation rate in a sequence with major lithologic and biotic changes is not warranted.

No large lithologic or benthic foraminiferal changes occurred below the base of the PETM and therefore we consider the glauconitic sandy interval directly below the CIE to be deposited under lower sedimentation rates in an environment comparable to that of the late Paleocene, namely a sediment-starved ramp. This reinterpretation of the sedimentation rates implies that the *Apectodinium* acme and the pre-PETM temperature rise preceded the PETM by a much longer time interval than earlier proposed, i.e. 40-45 and 20-25 kyr respectively (Fig. 4). In a similar way, the onset of the proposed latest Paleocene transgression is estimated at 165 kyr prior to the CIE, corresponding to the upper range of the proposed 20-200 kyr (Sluijs et al., 2008).

Sedimentation rates of the lowermost PETM interval are based on the position of the first occurrence of *T. bramlettei* relative to the CIE onset. The resulting estimates indicate a large increase at Wilson Lake (16.9 cm/kyr) and a smaller increase at Bass River (2.8 cm/kyr). These rates are assumed to be constant within the condensed interval at Bass River and equivalent interval at Wilson Lake. The remaining uppermost PETM interval at Wilson Lake falls within the upper part of the CIE "core" (<71.25 kyr; Stassen et al., 2009) and therefore minimum sedimentation rates are 21.4 cm/kyr, as it is unknown how much sediment is missing below the unconformity. Elevated sedimentation rates ( $\geq 10.0$  cm/kyr) are also inferred for the remaining equivalent PETM interval at Bass River.

#### 4. DISCUSSION

The lower Paleogene sedimentary regime of the New Jersey Coastal Plain is portrayed as a sediment-starved marine ramp (Browning et al., 2008). Benthic foraminiferal assemblages indicate stable, deep middle neritic (Wilson Lake) to outer neritic (Bass River), well-oxygenated (oxic) bottom water conditions during the latest Paleocene (environment 1 in Fig. 4). At Bass River, the percentage of planktic foraminifera and the dinoflagellate *Spiniferites*-*Areoligera* ratio increase in the 2-3 meter interval below the onset of the CIE, in combination with a decrease in weight percent sand and BIT index (relative amount of terrestrially derived branched tetraether lipids vs. marine derived isoprenoid tetraether lipids). These independent proxies point to a drop in energy levels and suggest a shift to more open marine outer neritic settings during the latest Paleocene (Sluijs et al., 2008; Harris et al., 2010). Based on these observations, a subtle sequence break has been placed around BR 359.0-359.1 m and the spatial difference between the sequence boundary and the CIE onset is interpreted as a transgression slightly preceding the onset of the PETM in the New Jersey Coastal Plain (Sluijs et al., 2008; Harris et al., 2010). Our higher resolution observations indicate no significant chan-

ges in benthic foraminiferal assemblages prior to the CIE and thus no evidence for changes in paleodepths (Fig. 4). The dinocyst assemblages reflect the distance of the site to the shoreline rather than the depth of the underlying water column, and the dinocyst distribution might be biased by coastal processes such as local surface turbulence. Based on the benthic foraminiferal changes, a major increase in paleodepth occurred directly at the onset of the PETM. Similar patterns are observed in the Egypt (Speijer and Wagner, 2002; Ernst et al., 2006) and Tunisia (Stassen et al., 2012), suggesting a global signal. Such an eustatic rise could be attributed to the melting of small Antarctic ice caps in combination with thermal expansion of the water column (Speijer and Wagner, 2002; Sluijs et al., 2008). These combined effects would have resulted in a rise of maximum 40 meter, yet a rise of 60 meter has been estimated for the New Jersey Coastal Plain on the basis of foraminiferal biogroups (Harris et al., 2010). These discrepancies indicate that the effects of varying taphonomic alterations and environmental changes on the depth distribution of benthic taxa across the P-E boundary need further investigation.

Benthic foraminiferal associations indicate that the uppermost Paleocene biogroups were gradually replaced by the PETM biogroups within the short transitional interval at Wilson Lake (environment 2 in Fig. 4). Species of both biogroups have relatively low carbon isotope values, placing the transitional fauna within the CIE. The increased proportion of outer neritic species (*A. acutus*, *P. prima* and *T. selmensis*) indicates an increase in water depth directly after the onset of the PETM, whereas the persistence of the Paleocene biogroups (e.g. *C. alleni*) suggests the continuation of sufficiently high oxygen levels. *Gavelinella beccariiiformis* is not present at this level, and has its highest occurrence below the onset of the CIE. *Gavelinella beccariiiformis* is widespread in Paleocene bathyal and even abyssal settings with upper range limits in oligotrophic oxic outer shelf settings (e.g. Widmark and Speijer, 1997; Thomas, 1998). The disappearance of this species from the New Jersey Coastal Plain is linked to the temperature rise or higher nutrient levels, as paleodepth increased and oxygen-limited conditions were established after the extinction of this species.

A significantly different environment (3) developed 4 kyr after the CIE onset, with the establishment of the poorly diverse *A. acutus*, *P. prima* and *T. selmensis* foraminiferal assemblage. It has been hypothesized that the deposition of the PETM clayey strata is due to the establishment of a (sub)tropical, river-dominated shelf, with large river discharges exporting clay and silt into the shelf and deposition into mud belts (Kopp et al., 2009). Nannoplankton assemblages indicate enhanced shelf eutrophication during the PETM (Gibbs et al., 2006b). The opportunistic PETM biogroup A is the benthic biotic response to the eutrophication and associated increased oxygen consumption caused by a large riverine input of nutrients and probably exacerbated by thermal and/or salinity driven stratification. High foraminiferal densities indicate the absence of suboxia or anoxia, but the high abundances of opportunistic

species and the absence of other benthic species indicate that stressed, dysoxic conditions were either continuous or occurred at high frequencies throughout the year. We attribute these conditions to long-term stratification that lasted 25-35 kyr and the main deposition of the clays was restricted to the middle shelf (Wilson Lake).

The opportunistic PETM biogroup A became less dominant at the time of increased supply of clay into the basin, coinciding with higher abundance of low-salinity tolerant dinocysts (Figs. 2 and 4). Higher deposition rates occurred on the entire New Jersey shelf (Wilson Lake and Bass River). Co-occurrence of the two foraminiferal biogroups in environment 4 suggests less oxygen limitation and/or different food sources. We envisage that climatic conditions might have created yearly flood events, transporting large amounts of suspended clay and fresh-water tolerant dinoflagellates far from the coastline. These freshwater plumes would have initiated episodic, probably seasonal stratification, causing temporal blooms of the opportunistic biogroup (A), whereas the other biogroup (B) may have flourished during the remainder of the year, explaining the co-occurrence of the two biogroups in environment 4 (Fig. 4). These environmental conditions lasted for the remainder of the studied CIE-interval.

## 5. CONCLUSIONS

Detailed correlation based on benthic foraminifera and dinocysts in addition to calcareous nannoplankton data made it possible to establish a robust and detailed comparison between the Wilson Lake and Bass River cores. This allowed new insights into the paleoenvironmental changes during the onset of the PETM.

- Uppermost Paleocene sediments were deposited at low sedimentation rates and represent oxic deep middle to outer neritic environments. No biotic shifts occurred within the benthic foraminiferal assemblages prior to the PETM.
- The most expanded onset of the PETM is encountered at Wilson Lake and reveals a transitional environment with a sufficiently ventilated water column. Paleodepth increased significantly at this level, yet there is no evidence for stratification of the water column.
- A time lag of 4000 years occurred between the onset of the CIE and the establishment of long-term water column stratification. An opportunistic benthic fauna is the result of almost continuously dysoxic bottom water conditions. Deposition of clay occurred mainly in the middle parts of the shelf (Wilson Lake).
- Seasonal salinity-driven stratification started ~25-35 kyr after the onset of the CIE, with deposition of clay in the middle (Wilson Lake) and outer parts of the shelf (Bass River).

## ACKNOWLEDGEMENTS

This research used samples and data of the United States Geological Survey (USGS) and ODP Leg 174AX, provided by the Integrated Ocean Drilling Program (IODP). Financial support was provided by grants from the KU Leuven Research

Fund and the Research Foundation Flanders (FWO) to Robert P. Speijer, and by the National Science Foundation (NSF) to Ellen Thomas (Grant OCE-0903014). We thank Kenneth Miller and an anonymous reviewer for constructive reviews.

## REFERENCES

- Agnini, C., Fornaciari, E., Raffi, I., Rio, D., Röhl, U. and Westerhold, T., 2007. High-resolution nannofossil biochronology of middle Paleocene to early Eocene at ODP Site 1262: Implications for calcareous nannoplankton evolution. *Marine Micropaleontology*, 64, 215-248.
- Browning, J.V., Miller, K.G. and Olsson, R.K., 1997. Lower to Middle Eocene benthic foraminiferal biofacies and lithostratigraphic units and their relationship to sequences, New Jersey Coastal Plain. In: Miller, K. G. and Snyder, S. W. (Editors), *Proceedings of the Ocean Drilling Program, Scientific Results*, 150X, pp. 207-228.
- Browning, J.V., Miller, K.G., Sugarman, P.J., Kominz, M.A., McLaughlin, P.P., Kulpecz, A.A. and Feigenson, M.D., 2008. 100 Myr record of sequences, sedimentary facies and sea level change from Ocean Drilling Program onshore coreholes, US Mid-Atlantic coastal plain. *Basin Research*, 20, 227-248.
- Cramer, B.S., Aubry, M.-P., Miller, K.G., Olsson, R.K., Wright, J.D. and Kent, D.V., 1999. An exceptional chronologic, isotopic, and clay mineralogic record of the latest Paleocene thermal maximum, Bass River, NJ, ODP 174AX. *Bulletin de la Société Géologique de France*, 170, 883-897.
- Ernst, S.R., Guasti, E., Dupuis, C. and Speijer, R.P., 2006. Environmental perturbation in the southern Tethys across the Paleocene/Eocene boundary (Dababiya, Egypt): Foraminiferal and clay mineral records. *Marine Micropaleontology*, 60, 89-111.
- Gibbs, S.J., Bown, P.R., Sessa, J.A., Bralower, T.J. and Wilson, P.A., 2006a. Nannoplankton extinction and origination across the Paleocene-Eocene Thermal Maximum. *Science*, 314, 1770-1773.
- Gibbs, S.J., Bralower, T.J., Bown, P.R., Zachos, J.C. and Bybell, L.M., 2006b. Shelf and open-ocean calcareous phytoplankton assemblages across the Paleocene-Eocene Thermal Maximum: Implications for global productivity gradients. *Geology*, 34, 233-236.
- Gibson, T.G., Bybell, L.M. and Owens, J.P., 1993. Latest Paleocene lithologic and biotic events in neritic deposits of southwestern New-Jersey. *Paleoceanography*, 8, 495-514.



- Harris, A.D., Miller, K.G., Browning, J.V., Sugarman, P.J., Olsson, R.K., Cramer, B.S. and Wright, J.D., 2010. Integrated stratigraphic studies of Paleocene-lowermost Eocene sequences, New Jersey Coastal Plain: Evidence for glacioeustatic control. *Paleoceanography*, 25, Pa3211.
- John, C.M., Bohaty, S.M., Zachos, J.C., Sluijs, A., Gibbs, S., Brinkhuis, H. and Bralower, T.J., 2008. North American continental margin records of the Paleocene-Eocene thermal maximum: Implications for global carbon and hydrological cycling. *Paleoceanography*, 23, PA2217.
- Kopp, R.E., Schumann, D., Raub, T.D., Powars, D.S., Godfrey, L.V., Swanson-Hysell, N.L., Maloof, A.C. and Vali, H., 2009. An Appalachian Amazon? Magnetofossil evidence for the development of a tropical river-like system in the mid-Atlantic United States during the Paleocene-Eocene thermal maximum. *Paleoceanography*, 24, PA4211.
- Liu, C., Browning, J.V., Miller, K.G. and Olsson, R.K., 1997. Paleocene benthic foraminiferal biofacies and sequence stratigraphy, Island Beach borehole, New Jersey. In: Miller, K. G. and Snyder, S. W. (Editors), *Proceedings of the Ocean Drilling Program, Scientific Results 150X*, pp. 267-275.
- McInerney, F.A. and Wing, S.L., 2011. The Paleocene-Eocene Thermal Maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the future. *Annual Review of Earth and Planetary Sciences*, 39, 489-516.
- Miller, K.G., 1997. Coastal Plain drilling and the New Jersey sea-level transect. In: Miller, K. G. and Snyder, S. W. (Editors), *Proceedings of the Ocean Drilling Program, Scientific Results, 150X*, pp. 3-11.
- Olsson, R.K. and Wise, S.W., 1987. Upper Paleocene to middle Eocene depositional sequences and hiatuses in the New Jersey Atlantic Margin. In: Ross, C. A. and Haman, D. (Editors), *Timing and Depositional History of Eustatic Sequences: Constraints on Seismic Stratigraphy*. Cushman Foundation for Foraminiferal Research 24, Houston, pp. 99-112.
- Röhl, U., Westerhold, T., Bralower, T.J. and Zachos, J.C., 2007. On the duration of the Paleocene-Eocene thermal maximum (PETM). *Geochemistry, Geophysics, Geosystems*, 8, Q12002.
- Schouten, S., Hopmans, E.C., Forster, A., van Breugel, Y., Kuypers, M.M.M. and Damste, J.S.S., 2003. Extremely high sea-surface temperatures at low latitudes during the middle Cretaceous as revealed by archaeal membrane lipids. *Geology*, 31, 1069-1072.
- Schouten, S., Hopmans, E.C., Schefuss, E. and Damste, J.S.S., 2002. Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? *Earth and Planetary Science Letters*, 204, 265-274.
- Sluijs, A., Bowen, G.J., Brinkhuis, H., Lourens, L.J. and Thomas, E., 2007a. The Paleocene-Eocene Thermal Maximum super greenhouse: biotic and geochemical signatures, age models and mechanisms of global change. In: Williams, M., Haywood, A. M., Gregory, F. J. and Schmidt, D. N. (Editors), *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*. The Micropalaeontological Society, Special Publications, London, pp. 323-350.
- Sluijs, A. and Brinkhuis, H., 2009. A dynamic climate and ecosystem state during the Paleocene-Eocene Thermal Maximum: inferences from dinoflagellate cyst assemblages on the New Jersey Shelf. *Biogeosciences*, 6, 1755-1781.
- Sluijs, A., Brinkhuis, H., Crouch, E.M., John, C.M., Handley, L., Munsterman, D., Bohaty, S.M., Zachos, J.C., Reichart, G.J., Schouten, S., Pancost, R.D., Sinninghe Damsté, J.S., Welters, N.L.D., Lotter, A.F. and Dickens, G.R., 2008. Eustatic variations during the Paleocene-Eocene greenhouse world. *Paleoceanography*, 23, PA4216.
- Sluijs, A., Brinkhuis, H., Schouten, S., Bohaty, S.M., John, C.M., Zachos, J.C., Reichart, G.J., Sinninghe Damsté, J.S., Crouch, E.M. and Dickens, G.R., 2007b. Environmental precursors to rapid light carbon injection at the Palaeocene/Eocene boundary. *Nature*, 450, 1218-U5.
- Speijer, R.P., Scheibner, C., Stassen, P. and Morsi, A.-M.M., 2012. Response of marine ecosystems to deep-time global warming: a synthesis of biotic patterns across the Paleocene-Eocene thermal maximum (PETM). *Austrian Journal of Earth Sciences*, this volume, 6-16.
- Speijer, R.P. and Wagner, T., 2002. Sea-level changes and black shales associated with the late Paleocene thermal maximum: organic-geochemical and micropaleontologic evidence from the southern Tethyan margin (Egypt-Israel). *Geological Society of America, Special Paper 356*, 533-549.
- Stassen, P., Dupuis, C., Steurbaut, E., Yans, J. and Speijer, R.P., 2012. Perturbation of a coastal Tethyan environment during the Paleocene-Eocene thermal maximum in Tunisia (Sidi Nasseur and Wadi Mezaz). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 317-318, 66-92.
- Stassen, P., Thomas, E. and Speijer, R.P., 2009. Benthic foraminiferal isotope records across the PETM from the New Jersey Coastal Plain. In: Crouch, E. M., Strong, C. P. and Hollis, C. J. (Editors), *Climatic and Biotic Events of the Paleogene (CBEP2009)*, extended abstracts from an international conference in Wellington, New Zealand. *GNS Science Miscellaneous Series 18*, pp. 135-137.

Thomas, E., 1998. Biogeography of the Late Paleocene benthic foraminiferal extinction. In: Aubry, M.-P., Lucas, S. H. and Berggren, W. A. (Editors), Late Paleocene-Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records. Columbia University Press, New York, pp. 214-243.

Thomas, E., Brinkhuis, H., Huber, M. and Röhl, U., 2006. An ocean view of the early Cenozoic Greenhouse World. *Oceanography*, 19, 94-103.

Widmark, J.G.V. and Speijer, R.P., 1997. Benthic foraminiferal ecomarker species of the terminal Cretaceous (late Maastrichtian) deep-sea Tethys. *Marine Micropaleontology*, 31, 135-155.

Zachos, J.C., Dickens, G.R. and Zeebe, R.E., 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature*, 451, 279-283.

Zachos, J.C., Schouten, S., Bohaty, S., Quattlebaum, T., Sluijs, A., Brinkhuis, H., Gibbs, S.J. and Bralower, T.J., 2006. Extreme warming of mid-latitude coastal ocean during the Paleocene-Eocene Thermal Maximum: Inferences from TEX86 and isotope data. *Geology*, 34, 737-740.

Received: 20 October 2011

Accepted: 24 March 2012

Peter STASSEN<sup>1\*)</sup>, Ellen THOMAS<sup>2)3)</sup> & Robert P. SPEIJER<sup>1)</sup>

<sup>1)</sup> Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, B-3001, Leuven, Belgium;

<sup>2)</sup> Department of Geology and Geophysics, Yale University, Whitney Avenue 210, New Haven, Connecticut 06520-8109, USA;

<sup>3)</sup> Earth and Environmental Sciences, Wesleyan University, Exley Science Center 459, Middletown, Connecticut 06459, USA;

<sup>\*)</sup> Corresponding author, peter.stassen@ees.kuleuven.be