

Chapter 6

Eustatic sea level rise during the Paleocene-Eocene thermal maximum

To assess sea level change across the latest Paleocene through the earliest Eocene, including the Paleocene-Eocene thermal maximum (PETM) global warming phase (55 Ma), we generated new organic-walled dinoflagellate cyst (dinocyst) assemblage data from the New Jersey shelf and the Arctic Ocean and combine these with previously published records from New Zealand. Combined with sediment size fraction data and relative supply of terrestrial versus marine organic matter, including biomarkers and palynomorphs, we use the dinocyst assemblages to reconstruct two third order sea level cycles through the latest Paleocene and earliest Eocene. The maximum flooding of the lower cycle correlates to Chron C25n, which correlates to previously presented sequence stratigraphies in the North Sea and in the southwest Pacific Ocean. Part of the transgression and the maximum flooding of the second cycle occurred during the PETM, and correlates to the classic Thanetian 5 (now Ypresian 1) sequence in the North Sea. Our records indicate that a significant PETM-related transgression began at least 20 kyrs before the globally recorded negative carbon isotope excursion. Transgressions within such little time are unlikely to have been caused by tectonic forcing. Coupled ocean-climate model simulations have recently indicated that even with 4-8 x pre-industrial CO₂ concentrations in the atmosphere, small ice-sheets were possibly present at high altitudes on Antarctica during the late Paleocene. Such models predict that melting of such ice sheets may have contributed 5-10 m of sea level rise. In addition, thermal expansion of sea water as a result of the ~5°C warming of the ocean likely contributed in a similar magnitude to the sea level rise across the PETM.

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Introduction

The Late Paleocene and particularly the Early Eocene were characterized by globally very high temperatures, likely associated to high greenhouse gas concentrations in the atmosphere, with no or only minor amounts of continental ice (e.g., Zachos et al., 2001). Superimposed on these warm conditions, a ~170 kyr (Röhl et al., in prep) episode of globally elevated temperatures occurred, called the Paleocene-Eocene thermal maximum (PETM, ~55.5 Ma ago). The base of the PETM is marked by a prominent negative carbon isotope excursion (CIE), widely recorded in sedimentary carbon of the terrestrial and marine realms (Kennett and Stott, 1991; Koch et al., 1992; Pagani et al., 2006). The CIE, by now used to approximate the Paleocene – Eocene boundary, reflects the injection of large amounts of ¹³C-depleted carbon into the exogenic carbon pool (Dickens et al., 1995; Chapter 1). The PETM is associated with large-scaled biotic turnover (Chapter 5), including benthic faunal extinctions (Thomas and Shackleton, 1996; Thomas, 1998), a global acme of the tropical dinoflagellate *Apectodinium* (Bujak and Brinkhuis, 1998; Crouch et al., 2001; Chapter 5; Appendix 1), turnovers in planktonic foraminifera (Kelly et al., 1996) and calcareous nannofossils (Bralower, 2002; Raffi et al., 2005) and migrations of terrestrial mammal (Bowen et al., 2002) and plant species (Wing et al., 2005).

Proxy-records have indicated that surface, as well as deep ocean waters warmed by ~5°C during the PETM (Chapter 3; Zachos et al., 2003; Tripati and Elderfield, 2005). Given the temperature-density relationship of seawater, such a rise in ocean temperatures should lead to a thermal expansion of ocean water equivalent to in the order of 3-5 meters of sea level rise. Furthermore, the presence of small Antarctic ice sheets even during the greenhouse conditions of the late Cretaceous and early Cenozoic has been invoked by various studies (e.g., DeConto and Pollard, 2003; Miller et al., 2005b). Thermal expansion, and the melting of such – if any - Antarctic ice sheets could have contributed to eustatic sea level rise at the PETM. In recent years, several studies have indeed recorded regional late Paleocene and early Eocene sea level variations, including those across the PETM, and sequence stratigraphies have been proposed (Haq et al., 1987; Miller et al., 1987; Haq et al., 1988; Gibson et al., 1993; Powell et al., 1996; Miller et al., 1998a; Speijer and Schmitz, 1998; Cramer et al., 1999; Gibson et al., 2000; Schmitz et al., 2001; Speijer and Morsi, 2002; Schmitz and Pujalte, 2003; Miller et al., 2005a; Miller et al., 2005b). Schmitz and colleagues (Schmitz et al., 2001; Schmitz and Pujalte, 2003) have argued for a sea level regression concomitant with the PETM based on lithological evidence in Spain. In contrast, Speijer and co-workers (Speijer and Schmitz, 1998; Speijer and Morsi, 2002), based on benthic foraminifer and ostracode assemblage evidence, suggest a transgression during the PETM in Egypt, which followed a latest Paleocene regression. However, thus far no larger scaled, cross hemisphere studies have been presented that would definitively assess and quantify PETM global sea level fluctuations.

In order to assess the role of sea level change during the late Paleocene, and the PETM in particular, we have studied Ocean Drilling Program Leg 174AX Site 'Bass River' and United States Geological Survey (USGS) borehole 'Wilson Lake' from the New Jersey Shelf at ~40°N paleolatitude, and Integrated Ocean Drilling Program Expedition 302 (or Arctic Coring Expedition) from the Lomonosov Ridge in the Arctic Ocean (Fig. 1). The cores recovered from these sites bear relatively expanded PETM successions, which are likely to have been influenced by changes in sea level due to the shallow marine setting in which they formed (Cramer et al., 1999; Gibbs et al., 2006; John et al., in prep; Chapters 3 and 4). Subsidence of these passive margins during the late Paleocene through early Eocene was slow relative to the time scales of third-order sea level cycles (Miller, 1997; Miller et al., 1998b; Backman et al., 2006). We combine the data of these sites with published records from New Zealand (Crouch and Brinkhuis, 2005) and correlate them to the North Sea sequence stratigraphy (Powell et al., 1996; Bujak and Brinkhuis, 1998) and the East Tasman Plateau (Röhl et al., 2004a) (Fig. 1). This compilation enables us to study sea level trends at continental margins of four continents, which will result in the recognition of global sea level variations across the PETM. In addition, this allows assessing the timing of these fluctuations relative to the CIE. We apply multiple proxies to assess sea level changes at these sites.

The sediments from all these sites have abundant organic-walled dinoflagellate cysts (dinocysts) suitable for paleoenvironmental applications (Chapters 3 and 4; Bybell et al., 2001; Crouch et al., 2003b; Crouch and Brinkhuis, 2005). Dinocysts are potentially useful to reconstruct eustatic sea level changes through the PETM. Most organic cyst-forming dinoflagellates are adapted to neritic settings and are very sensitive to even small changes in ecology (e.g., Dale, 1996). The assemblages of their preservable cysts – which are mostly produced after sexual reproduction – from the sediments, hence, reflect the physio-chemical characteristics of the surface waters (Appendix 1). With sea level rise (/lowering), watermasses at a specific site tend to exhibit more offshore (/ inshore) characteristics, which is recorded in the dinocyst assemblages. Dinocyst assemblages have, hence, been successfully employed to reconstruct the relative influence of nearshore and offshore waters, respectively, and thereby sea level fluctuations throughout the Cenozoic (e.g., Brinkhuis, 1994; Powell et al., 1996; Röhl et al., 2004b; Pross and Brinkhuis, 2005; Torricelli et al., 2006; Appendix 1), including the PETM (Powell et al., 1996; Bujak and Brinkhuis, 1998; Crouch and Brinkhuis, 2005).

Along with dinocyst data, we present the bulk sediment size fraction weight percent >63 μm (wt. % sand) data from (John et al., in prep) to reconstruct energy levels of the sedimentary environment on the sites from New Jersey. Similar data were generated by (Cramer et al., 1999) for Bass River, showing that in the intervals where the wt. % sand is high, this fraction consists for a large part of glauconite and quartz grains that have been eroded and transported from

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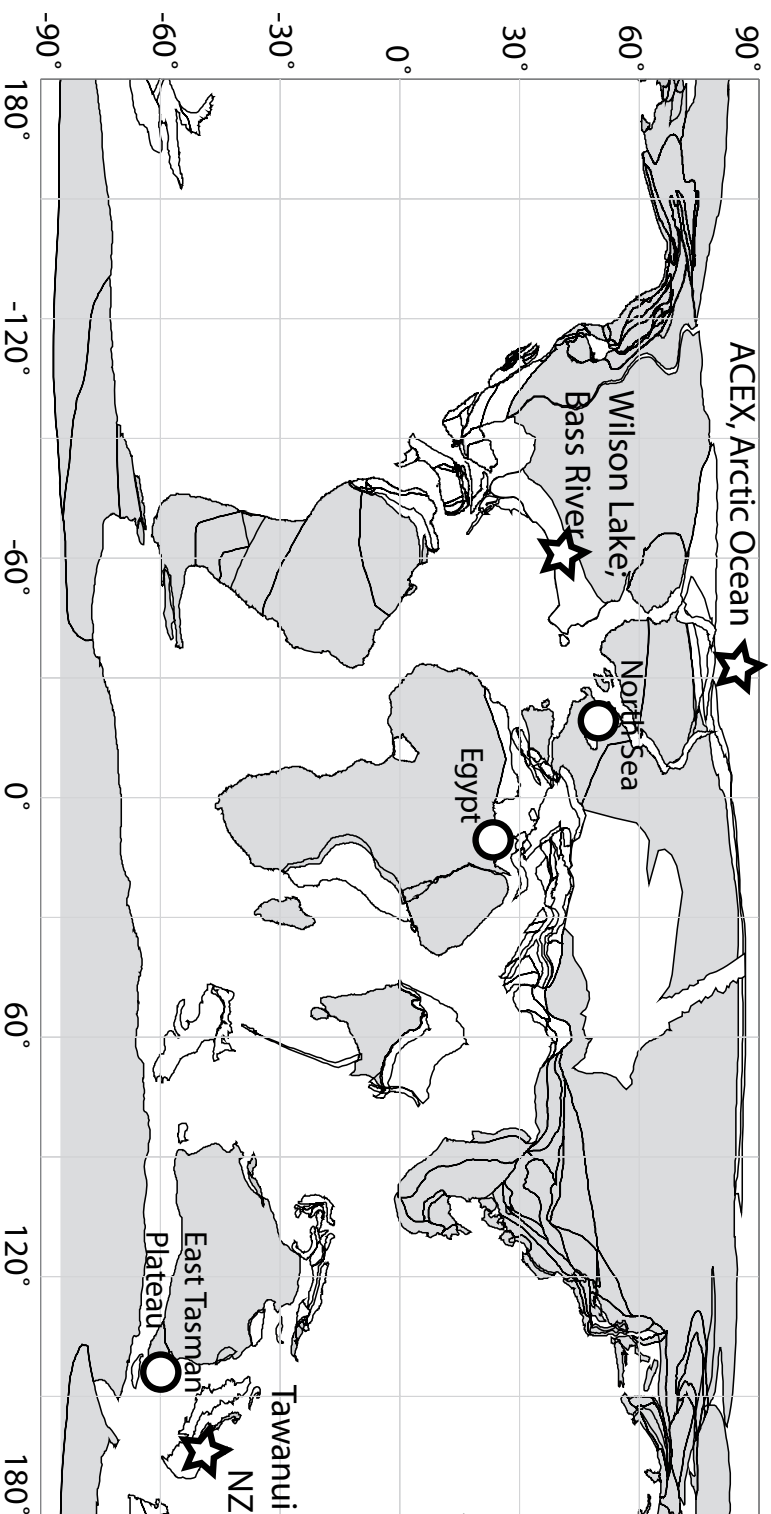


Figure 1. Locations of the studied sites (stars), and sites with previously published latest Paleocene and earliest Eocene sea level records (circles), including the Gebel Duwi site, Egypt (Speijer and Morsi, 2002) the North Sea (Powell et al., 1996; Bujak and Brinkhuis, 1998) and East Tasman Plateau (Rohl et al., 2004) within a paleogeographic reconstruction of the Earth at PETM times (source: <http://www.odsn.de/odsn/services/paleomap/paleomap.html>). Estimated regions of submerged continental shelves are indicated by black lines surrounding white areas.

older exposed marine deposits. On the Bass River section we also measured the Branched and Isoprenoid Tetraether (BIT) index, which indicates the amount of river-derived terrestrial organic matter relative to marine organic matter (Hopmans et al., 2004). BIT data from the Lomonosov Ridge and the Wilson Lake sites are adapted from Chapters 3 and 4, respectively. Finally, we use the abundance of terrestrially-derived palynomorphs (thereby excluding saccate pollen, which are often long-distance transported by wind) relative to marine-derived palynomorphs to assess proximity to the coast.

Age models and sedimentation rates

For Wilson Lake (Gibbs et al., 2006; Chapter 4), the ACEX section (Chapter 3) and the Tawanui section (Crouch et al., 2001) we follow previously published age models, which are primarily based on the identifications of the CIEs, and nannofossil and/or dinocyst biostratigraphy. At Bass River, the record includes a relatively complete uppermost Paleocene section and we mostly adapt the age model of Cramer et al., 1999) which is based on calcareous nannofossil biostratigraphy, paleomagnetism and the identification of the CIE. This age model is relatively consistent although it has some local discrepancies between nannofossil zones and paleomagnetism (Cramer et al., 1999). Moreover, the only short (~0.5 Ma; Westerhold et al., submitted) Chron C25n appears very thick relative to the thickness of the very long interval (~1.3 Ma) between the onset of C24n and the CIE. The reversal between Chrons C25n and C24r was identified mostly based on samples with relatively poor demagnetization patterns, so the location of that reversal may be slightly higher or several meters lower (Cramer et al., 1999). For a narrower restriction of the position of the CIE than was previously achieved, we use the stable bulk carbonate-derived carbon isotope ($\delta^{13}\text{C}_{\text{BC}}$) data from John et al. (in prep).

Stable carbon isotope, and dinocyst stratigraphy indicates that the upper bound of the PETM at Bass River (Fig. 2) and Wilson Lake (Fig. 3) is truncated in a sequence boundary, which is corroborated by a glauconite-rich unit. Sediments above this sequence boundary have been dated within the ~2 Myr younger (Westerhold et al., submitted) Chron C24n based on biostratigraphy and magnetostratigraphy (Cramer et al., 1999; Gibbs et al., 2006). This identification of this chron is supported by the occurrence of dinocysts that originated close to Eocene Thermal Maximum 2 (Chapter 2), such as *Wetzeliella mackelfeldensis*.

Using the stratigraphic thickness of the CIE and the by now reasonably restricted duration of ~170 kyr of the CIE (Röhl et al., in prep), sedimentation rates can be calculated for our study sites. However, because of the coring gaps this remains difficult for the ACEX section. Considering the small magnitude of the CIE at Tawanui (Kaiho et al., 1996; Crouch et al., 2003b; Crouch and Visscher, 2003), its completeness at the base may be questioned. The CIE at this condensed

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bathyal section is approximately 80 cm thick, implying sedimentation rates of about 0.5 cm.kyr⁻¹. At Bass River, approximately 100 kyr of the PETM is represented in ~10 meter of section (Chapter 7), implying sedimentation rates of approximately 10 cm.kyr⁻¹. Sedimentation rates at Wilson Lake are estimated to 8.4 cm.kyr⁻¹ (Gibbs et al., 2006).

Material and Methods

Material

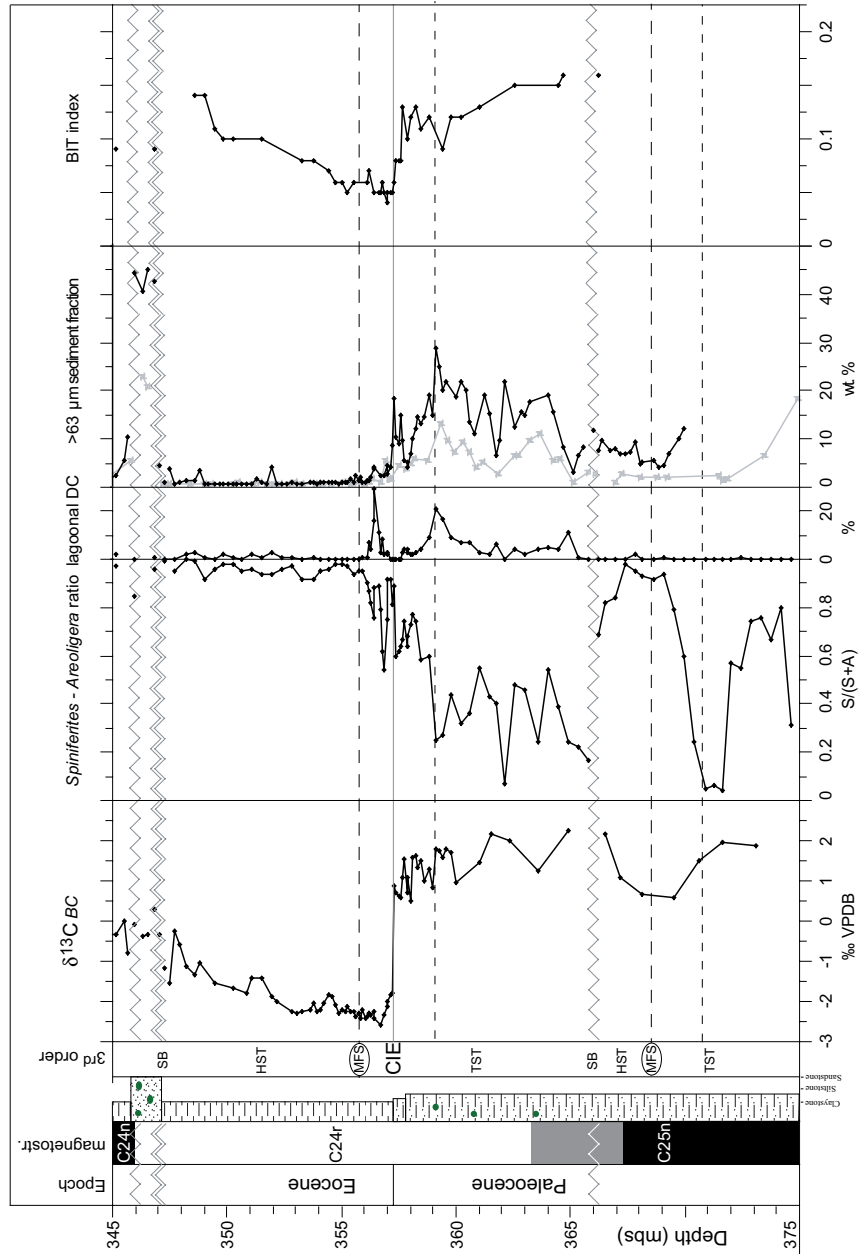
We have used United States Geological Survey (USGS) borehole ‘Wilson Lake’, the Ocean Drilling Program Leg 174AX Site ‘Bass River’ from the New Jersey Shelf, the Integrated Ocean Drilling Program Expedition 302 (or Arctic Coring Expedition, ACEX) Hole 4A from the Lomonosov Ridge in the Arctic Ocean and the Tawanui section in New Zealand (Fig. 1). At all these sites, the upper Paleocene through lower Eocene represents organic rich siliciclastic mudstone and claystone, which yields rich palynomorph assemblages. Except for the ACEX section, the sites bear some calcareous microfossils, including nannofossils and foraminifera. Lithological and micropaleontological information indicated that the New Jersey sites were located on the shelf during the PETM (Gibson et al., 1993; Gibson and Bybell, 1994; Cramer et al., 1999; Gibson et al., 2000; Bybell et al., 2001), these sites were located on the shelf during the PETM. The ACEX site on the Lomonosov Ridge was also close to land, given the high terrestrial component of the sediments (Chapter 3, Backman et al., 2006). The Tawanui section in New Zealand was located on the upper slope (Kaiho et al., 1996; Crouch et al., 2003b; Crouch and Brinkhuis, 2005).

Methods

Palynological processing was performed using standard methods (c.f., Sluijs et al., 2003). Briefly, samples were freeze-dried and a known amount of *Lycopodium* spores were added to ~10g of material. Then, the samples were treated with 30% HCl and twice with 38% (HF) for carbonate and silicate removal, respectively. Residues were sieved using a 15- μ m nylon mesh to remove small particles. To break up clumps of residue, the sample was placed in an ultrasonic bath for a maximum of 5 minutes, sieved again, and subsequently concentrated to 1 ml, of which 7.5-10 μ l was mounted on microscope slides. Slides were counted to a minimum of 200 dinocysts.

Following most previous studies that used dinocyst assemblages to reconstruct changes in proximity to the coast (Brinkhuis, 1994; Pross and Brinkhuis, 2005; Appendix 1), we use the relative abundance of Gonyaulacoid dinocyst taxa. The distribution of Peridinioid dinoflagellates is less sensitive to sea level changes, likely because they are relatively euryhaline and react predominantly to changes in trophic level, which is not always directly linked to sea level variations (e.g., Reichart

Figure 2. Bass River, New Jersey; magnetostratigraphy, sequence stratigraphic interpretation, bulk carbonate (BC) $\delta^{13}C$, *Spiniferites* / *Areoligera* ratio, percentage lagoonal dinocysts (DC), % sand and BIT index data through the latest Paleocene - earliest Eocene. Paleomagnetic and % sand data in grey are from Cramer et al. (1999). mbs = meters below surface, SB = Sequence Boundary, MFS = maximum flooding surface, HST = Highstand Systems Tract, TST = Transgressive Systems Tract, VPDB = Vienna Pee Dee Belimnite.



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and Brinkhuis, 2003; Sluijs et al., 2003; Röhl et al., 2004b)). Dominance of the *Areoligera* cpx. indicates inner neritic environments (Brinkhuis, 1994; Pross and Brinkhuis, 2005), while the *Spiniferites* cpx. is mostly observed in neritic deposits with increasing relative abundances at outer neritic localities (Brinkhuis, 1994; Pross and Brinkhuis, 2005; Torricelli et al., 2006). We use the abundance of the inner neritic *Areoligera* cpx relative to that of the neritic *Spiniferites* cpx, presented as the S/A index. This index represents the closed-sum ratio $Spiniferites / (Spiniferites + Areoligera)$ and, hence, is not biased by variations in abundance of Peridinioid taxa. Hence, low S/A index values represent a typical inner neritic setting, while high numbers indicate a more outer neritic setting. Although variations in *Spiniferites* abundance occur, most fluctuations in the S/A index are due to variations in *Areoligera* abundance. Members of the family Goniodomaceae, in our samples represented by *Eocladopyxis* and *Polysphaeridium* spp., are mostly recorded lagoonal conditions (Bradford and Wall, 1984; Brinkhuis, 1994; Reichart et al., 2004; Pross and Brinkhuis, 2005). We use the abundance of this group within the whole dinocyst assemblage as an indicator for lagoonal conditions.

For the Branched and Isoprenoid Tetraether (BIT) index analyses, powdered and freeze-dried sediments (~20 g dry mass) were extracted with dichloromethane (DCM)/methanol (9:1) by using the Dionex accelerated solvent extraction technique. The extracts were separated by Al_2O_3 column chromatography using hexane/DCM (9:1) and DCM/methanol (1:1) to yield the apolar and polar fractions, respectively. By means of high pressure liquid chromatography / mass spectrometry, the polar fractions were analyzed for tetraether lipids, which were used to calculate the BIT index.

Results

New Jersey sites

Palynomorphs are abundant and well preserved throughout the Bass River and Wilson Lake records. Dinocysts outnumber by far other palynomorphs, and among them, *Apectodinium*, *Areoligera* and *Spiniferites* are quantitatively significant. In addition, representatives of the likely fresh water, and/or fresh water tolerant Peridinioid genera such as *Senegalinium* are important (Chapter 7). Abundances of terrestrial palynomorphs at these sites are very low and variations therein insignificant to track sea level variations. BIT index values are generally very low, but duplicate analyses showed that variations are reproducible, allowing us to assess the relative amount of terrestrially-derived organic matter supply by rivers relative to the amount of marine organic matter.

At Bass River, an increase in the S/A index at 370 meters below surface (mbs) points to a significant increase in the position of the site relative to the coast (Fig. 2). This shift correlates to decreasing wt. % sand, together implying a phase of

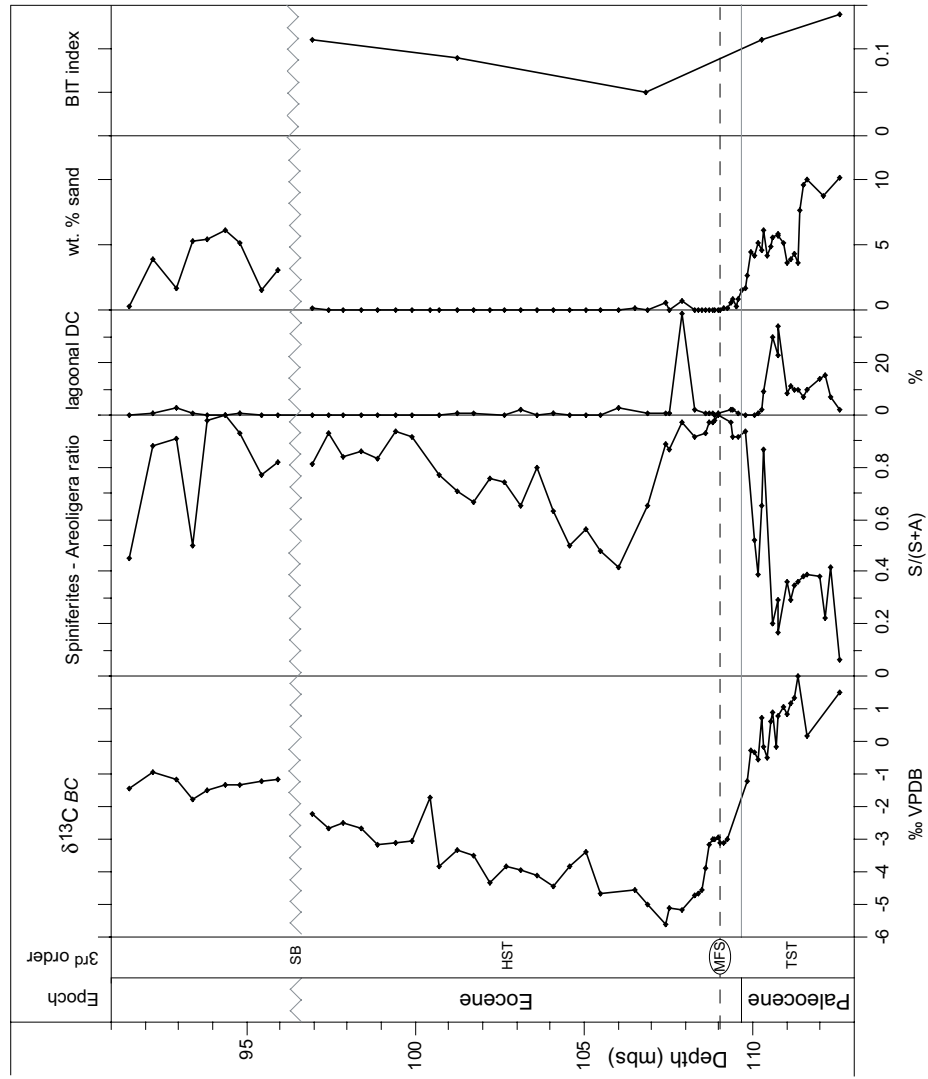


Figure 3. Wilson Lake, New Jersey; sequence stratigraphic interpretation, bulk carbonate (BC) $\delta^{13}\text{C}$, *Spiniferites* / *Areoligera* ratio, percentage lagoonal dinocysts (DC), % sand and BIT index data through the latest Paleocene - earliest Eocene. mbs = meters below surface, SB = Sequence Boundary, MFS = maximum flooding surface, HST = Highstand Systems Tract, TST = Transgressive Systems Tract, VPDB = Vienna Pee Dee Belemnite.

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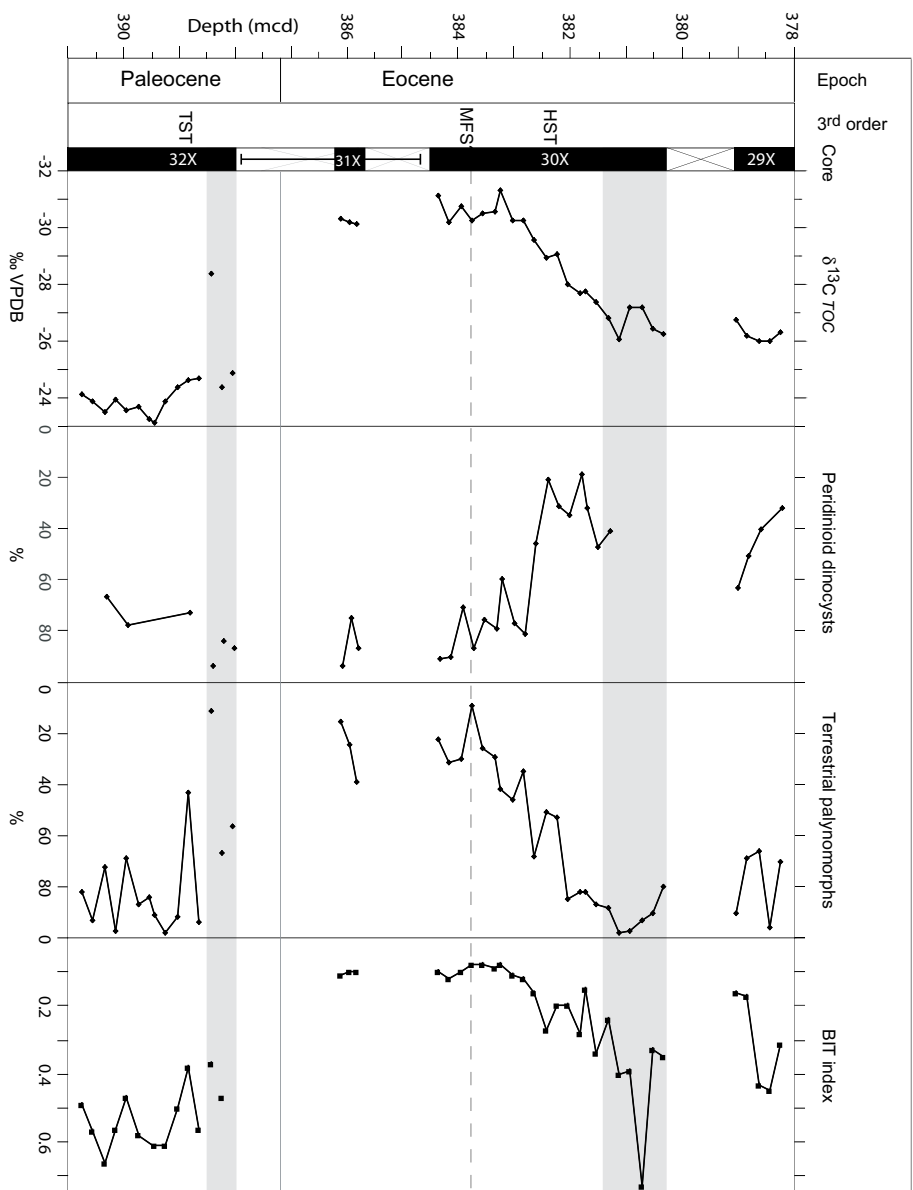


Figure 4. Lomonosov Ridge, Arctic Ocean; sequence stratigraphic interpretation, total organic carbon (TOC) $\delta^{13}C$, percentage peridinioid dinocysts, percentage terrestrial palynomorphs and BIT index data through the latest Paleocene – earliest Eocene. mcd = meters composite depth, MFS = maximum flooding surface, HST = Highstand Systems Tract, TST = Transgressive Systems Tract, VPDB = Vienna Pee Dee Bellinrite.

transgression. The interval between the top of Chron C25n and the CIE – an interval spanning ~1.3 Million years (Westerhold et al., submitted) – is less than 10m. This would imply sedimentation rates of less than 1 cm.kyr⁻¹, which is extremely low for a neritic site, and much lower than the average sedimentation rates during the PETM. Hence, a sequence boundary-driven hiatus is to be assumed here. We thus infer a third-order sequence boundary at the strong decreases in S/A index at ~366 mbs, which is close to the onset of consistently present lagoonal dinocysts (Fig. 2). No biostratigraphic constraints are available to estimate the duration of the hiatus associated to the sequence boundary, but considering the thin interval of Chron C24r below the CIE, it is probably in the order of several 100s of kyr. During the subsequent TST, the BIT index gradually decreases, while fluctuations in S/A index sometimes coincide with fluctuating wt. % sand and % lagoonal dinocysts, potentially indicating 4th order sea level fluctuations.

At Bass River the S/A index increases significantly between ~359 and 355m (Fig. 2). Moreover, the % lagoonal taxa decreases, as well as the wt. % sand – suggesting a decrease in the energy levels of the sedimentary environment – and BIT index – evidencing a decreasing relative supply of terrestrial organic carbon. These trends are consistent with transgression and we place the mfs at the maximum in S/A index, and minima in wt% sand and BIT index. These results imply that this transgression is initiated ~2m below and the maximum flooding occurred ~1m above the onset of the CIE at 375.3 mbs. Assuming sedimentation rates of 10.4 cm.kyr⁻¹ (Chapter 7), the transgression initiated approximately 20 kyr before the CIE and continued for ~10 kyrs after the onset of the CIE. Evidence for sea level lowering during the upper parts of the CIEs is suggested by higher values of the BIT index, but not evident in dinocysts or wt. % >63 μ m sediment fraction. The upper bound of the PETM is truncated in a second third-order sequence boundary.

At the bottom of the Wilson Lake section, the S/A index increases (Fig. 2), the % lagoonal taxa decreases, as well as the wt. % sand and BIT index (Fig. 3). Based on these trends, the two peak abundances of lagoonal dinocysts and the position of the CIE, this section can be correlated to Bass River. Also at Wilson Lake, the transgression is initiated ~1.5 m below the onset of the CIE, although the location of negative step is less well constrained at Wilson Lake than at Bass River (Chapter 4; Gibbs et al., 2006). We infer the mfs at the maximum in S/A index, and minima in wt% sand and BIT index, located ~80 cm above the onset of the CIE (Fig. 3). Assuming sedimentation rates of 8.4 cm.kyr⁻¹ for the PETM at this site (Gibbs et al., 2006), the transgression started ~20 kyr before the CIE, with the maximum flooding ~10 kyrs after the onset of the CIE, comprising similar estimates as at Bass River.

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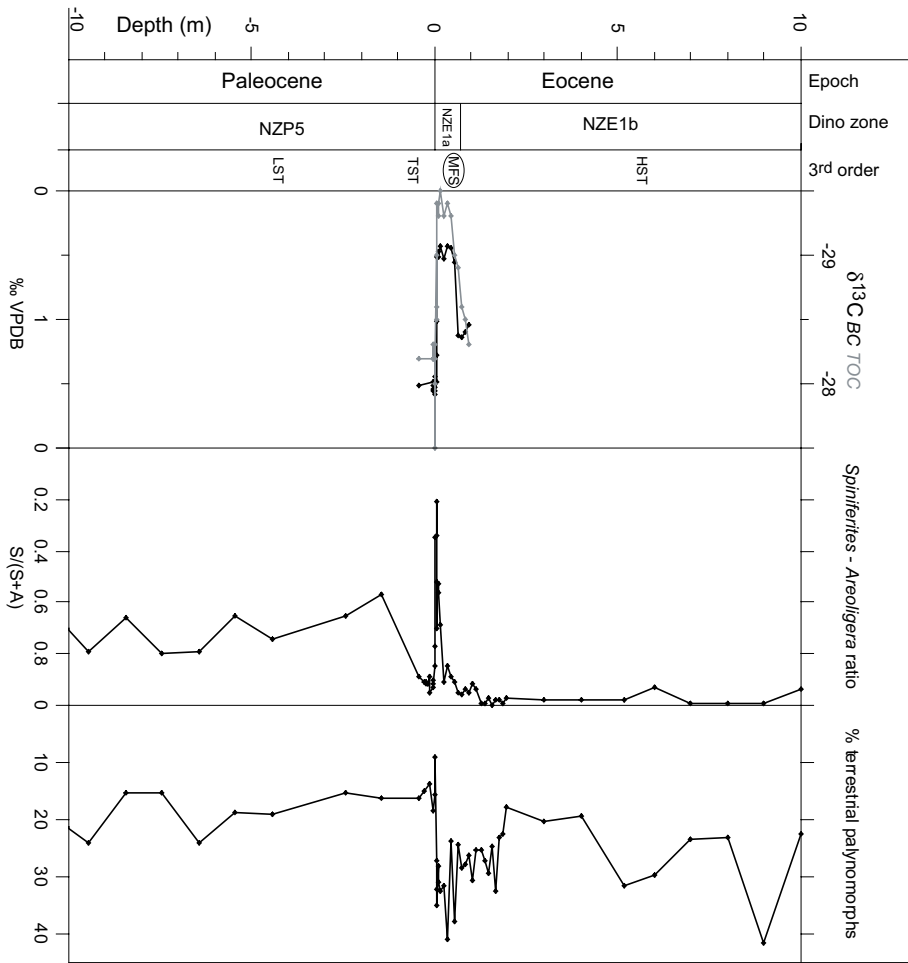


Figure 5. Tawannui, New Zealand; sequence stratigraphic interpretation, bulk carbonate (BC) and total organic carbon (TOC) $\delta^{13}C$, *Spiniferites* / *Areoligera* ratio and percentage terrestrial palynomorphs through the latest Paleocene – earliest Eocene. mbs = meters below surface, SB = Sequence Boundary, MFS = maximum flooding surface, HST = Highstand Systems Tract, TST = Transgressive Systems Tract, VPDB = Vienna Pee Dee Belemnite.

At both sites, following standard sequence stratigraphy models, sedimentation rates on the shelf were likely relatively low during this transgression. Hence, the 20 kyr offset between the onset of transgression and the onset of the CIE represents a minimum estimate.

Arctic Ocean

Late Paleocene through earliest Eocene palynological assemblages in the ACEX section are dominated by terrestrial material, with many samples yielding >99% terrestrial palynomorphs. This general situation is significantly different during the PETM, when the input of terrestrial palynomorphs and organic biomarkers relative to those of marine origin decreased significantly (Fig. 4). Dinocyst assemblages are dominated by Peridinioid taxa, which reflect the low salinities and eutrophic conditions through the PETM in the Arctic Ocean (Chapter 3; Pagani et al., 2006). Salinities are so low throughout the event that Gonyaulacoid taxa commonly used to reconstruct proximal-distal trends are quite rare. For this reason, variations in proximity to the coast are difficult to extract from the dinocyst assemblages (Chapter 3). However, clear decreases in both the relative abundance of terrestrial palynomorphs and in the BIT index are likely caused by a more distal position of the site. Due to recovery problems, it is, however, not possible to assess the timing of the onset of the transgression relative to the CIE at this site.

New Zealand

The Tawanui section yields rich palynological assemblages including marine as well as terrestrial palynomorphs (Crouch et al., 2003b; Crouch and Visscher, 2003; Crouch and Brinkhuis, 2005). Considering that the site is located on the paleocontinental slope of the New Zealand margin (Kaiho et al., 1996), most of the dinocysts that are characteristic of neritic settings have likely been transported off the shelf (Crouch et al., 2003b). Nevertheless, also at this site the S/A index shows an increase across the CIE (Fig. 5), implying that the source of *Areoligera* cpx was further away from the site relative to the source of *Spiniferites* cpx. The short-lived pulse of *Areoligera* cpx close to the onset of the CIE corresponds to a redeposited glauconite-rich layer (Kaiho et al., 1996), and has been interpreted as greater downslope transport of inner neritic material (Crouch et al., 2003b). The rise in % terrestrial palynomorphs at the PETM is attributed to an increase in terrestrial discharge at this section (Crouch et al., 2003b). Hence, the increased S/A index at Tawanui can be ascribed to a third-order transgression with the mfs located within the PETM.

Discussion

Based on variations in S/A index, wt. % coarse fraction, % terrestrial palynomorphs and BIT index we infer eustatic sea level fluctuations in the latest

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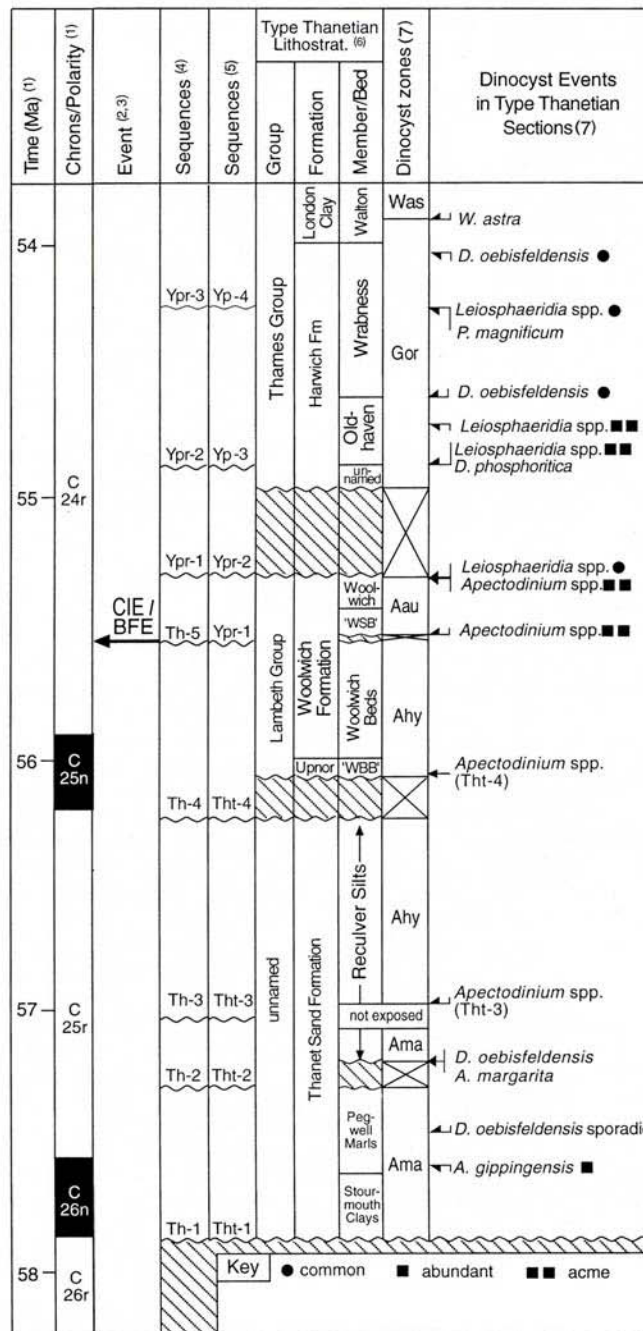


Figure 6. North Sea sequence stratigraphy compiled by Bujak and Brinkhuis (1998). 1 After Berggren et al. (1995); 2, 3 Kennett and Stott (1991); Thomas and Shackleton (1996); 4 Powell et al. (1996); 5 revised names of the sequences of Powell et al. (1996), due to the changed position of the Paleocene-Eocene boundary; 6 after Knox et al. (1994); 7 after Powell (1992); Powell et al. (1996).

Paleocene through earliest Eocene. At Bass River, we have identified two third-order sea level sequences during the latest Paleocene and earliest Eocene. The maximum flooding associated with the lower one occurred during Chron C25n (Fig. 2), which allows correlation to the classic sequence Thanetian 4 in the North Sea, although the magnetostratigraphy in the North Sea is poorly defined (Stover and Hardenbol, 1994; Powell et al., 1996; Bujak and Brinkhuis, 1998; Fig. 6). Furthermore, a maximum flooding surface was recently identified within Chron C25n in a shallow marine sequence from the southwestern Pacific on the East Tasman Plateau (Röhl et al., 2004a), indicating that this sea level cycle is global in nature. We infer a third-order sequence boundary near the top of Chron C25n based on a sharp decrease in S/A index. No firm restrictions exist on the length of the hiatus at this level but it is likely in the order of several 100s of kyrs.

During the later part of Chron C24r, the records from the New Jersey Shelf, the Lomonosov Ridge and the New Zealand margin consistently point to a third-order sea level transgression with the mfs during the PETM. The maximum flooding and subsequent highstand correlates with the Thanetian 5 sequence (Stover and Hardenbol, 1994; Powell et al., 1996; Bujak and Brinkhuis, 1998). Since the redefinition of the Paleocene-Eocene boundary sequence Thanetian 5 is located in the earliest Eocene and we refer to it as sequence Ypresian 1 in Fig. 6. Transgression at the PETM has previously been suggested by several authors. Speijer and Morsi (2002) argued for a ~30m transgression during the PETM in the Egypt based on ostracode assemblage evidence. Qualitatively, this interpretation is consistent with benthic foraminifer assemblage, lithological and dinocyst evidence from the Tethyan margins (Speijer and Schmitz, 1998; Speijer and Wagner, 2002; Crouch et al., 2003a; Gavrillov et al., 2003). Palynological and sequence stratigraphic evidence for transgression during the PETM is also available from the North Sea (Powell, 1992; Powell et al., 1996; Bujak and Brinkhuis, 1998; Steurbaut et al., 2003) and New Zealand (Crouch and Brinkhuis, 2005). Moreover, in the Turgay Straight the *Apectodinium augustum* interval, which marks the PETM (Powell et al., 1996; Bujak and Brinkhuis, 1998; Chapter 7), represents a clay interval associated with a transgression and a highstand phase (Iakovleva et al., 2001; Radinova et al., 2001). Together these records imply that eustatic sea level rise occurred across the PETM.

A sea level regression inferred from deposits in northern Spain (Schmitz and Pujalte, 2003) likely occurred prior to the PETM and was followed by transgression at the PETM (Pujalte and Schmitz, 2006). The interpretation of regression prior to the PETM is consistent with observations from the Tethys (e.g., Speijer and Morsi, 2002; Pujalte and Schmitz, 2006). Unless this episode correlates to sea level lowering during the lower part of C24r, we have not found evidence for this on the New Jersey Shelf, the Arctic Ocean or New Zealand, suggesting that this is a phenomenon related to regional tectonics in the Tethyan realm.

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Recently it was proposed that the isolation of a large epicontinental seaway, followed by desiccation and bacterial respiration of the aerated organic matter is a potential mechanism for the rapid release of large amounts of CO₂ (Higgins and Schrag, 2006). The primary epicontinental sea at the root of this hypothesis is located in Eurasia, representing the Turgay Straight, Southeastern Europe and South Asia. However, instead of paleosols, expanded marine deposits have been documented from the PETM of these regions (e.g., Iakovleva et al., 2001; Crouch et al., 2003a; Akhmetiev and Beniamovski, 2004), thus seriously questioning desiccation of the area.

Many authors have proposed that the Late Paleocene and Early Eocene greenhouse world lacked continental ice sheets of a size that would be significant for sea level changes (e.g., (Zachos et al., 2001), but discussion exists on this (e.g., Miller et al., 2005b). In their model, DeConto and Pollard (2003) assess the sensitivity of Antarctic ice sheets in the Eocene to varying atmospheric CO₂ concentrations. They conclude that ice sheets equivalent to up to 20 m of sea level change the potentially existed during the early Paleogene greenhouse world. In the latest Paleocene, these ice sheets were equivalent of ~5-10 meters of sea level according to Miller et al. (2005b). If so, the PETM transgression may have been in part glacioeustatic. For the PETM, another mechanism of sea level rise is thermal expansion of ocean water due the quasi-uniform ~5°C global warming (Chapter 3; Zachos et al., 2003; Tripathi and Elderfield, 2005). Calculation of the magnitude of such thermal expansion is complex but is in the order of a few to 5 meters. On time scales of the transgression described in this study, these are the only mechanisms known to play a significant role in sea level changes. This implies that third-order sea level changes during the late Paleocene and the early Eocene, including the one at the PETM, are unlikely to have been larger than ~10m, unless the size of continental ice sheets has been severely underestimated.

Conclusions

Based on palynological, lithological, and organic geochemical evidence from marginal marine sediment from the New Jersey Shelf, the Arctic Ocean and New Zealand and published sequence stratigraphies from the southwest Pacific Ocean and the North Sea we infer two eustatic sea level cycles in the latest Paleocene through the earliest Eocene. The maximum flooding of the first cycle occurred during Chron C25n. Significant sea level rise associated with the second cycle began at least 20 kyrs before the CIE and its maximum flooding occurred approximately 10 kyrs after the onset of the CIE. Several meters of transgression during the PETM can be attributed to thermal expansion of sea water as a result of the ~5°C warming of the ocean. However, the sea level variations not associated with the PETM corroborate the idea that small ice-sheets were present on high altitudes on Antarctica during the late Paleocene.