

The Palaeocene-Eocene Thermal Maximum super greenhouse: biotic and geochemical signatures, age models and mechanisms of global change

Appy Sluijs^{1*}, Gabriel J. Bowen², Henk Brinkhuis¹, Lucas J. Lourens³, and Ellen Thomas⁴

¹ Palaeoecology, Institute of Environmental Biology, Utrecht University. Laboratory of Palaeobotany and Palynology. Budapestlaan 4, 3584 CD Utrecht, The Netherlands

² Earth and Atmospheric Sciences, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, USA

³ Faculty of Geosciences, Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

⁴ Center for the Study of Global Change, Department of Geology and Geophysics, Yale University, New Haven CT 06520-8109, USA; also at Department of Earth & Environmental Sciences, Wesleyan University, Middletown, CT

* Corresponding Author: A.Sluijs@bio.uu.nl

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Abstract

The Palaeocene – Eocene thermal maximum (PETM), a geologically brief episode of global warming associated with the Palaeocene – Eocene boundary, has been studied extensively since its discovery in 1991. The PETM is characterized by a globally quasi-uniform 5-8°C warming and large changes in ocean chemistry and biotic response. The warming is associated with a negative carbon isotope excursion (CIE), reflecting geologically rapid input of large amounts of isotopically light CO₂ and/or CH₄ into the exogenic (ocean-atmosphere) carbon pool. The biotic response on land and in the oceans was heterogeneous in nature and severity, including radiations, extinctions and migrations. Recently, several events that appear similar to the PETM in nature, but of smaller magnitude, were identified to have occurred in the late Palaeocene through early Eocene, with their timing possibly modulated by orbital forcing. Although debate continues on the carbon source, the mechanisms that caused the input, the mechanisms of carbon sequestration, and the duration and pacing of the event, the research carried out in the last 15 years has provided new constraints and spawned new research directions that will lead to improved understanding of PETM carbon cycle and climate change.

A distinct period of extreme global warmth was initiated close to the boundary between the Palaeocene and Eocene epochs, approximately 55.5 Ma ago (Gradstein *et al.* 2004). This event, termed the Palaeocene-Eocene Thermal Maximum (PETM), occurred during a time of generally warm, “greenhouse” climate conditions, but stands out against the background warmth as an abrupt and short-lived spike in global temperatures. Evidence for global warming is preserved by the TEX₈₆’ temperature proxy (Sluijs *et al.* 2006; Zachos *et al.* 2006), oxygen isotope ($\delta^{18}\text{O}$) excursions in marine foraminiferal calcite (Fig. 1) (Kennett and Stott 1991; Thomas *et al.* 2002) and terrestrial carbonates (Koch *et al.* 1995), increased Mg/Ca values in planktic and benthic foraminifera (Zachos *et al.* 2003; Tripathi and Elderfield 2005), poleward migrations of

(sub)tropical marine plankton (Kelly *et al.* 1996; Crouch *et al.* 2001) and terrestrial plant species (Wing *et al.* 2005), and mammal migrations across high northern latitudes (Bowen *et al.* 2002; Bowen *et al.* 2006; Smith *et al.* 2006). Associated with the warming is a negative 2.5-6‰ carbon isotope ($\delta^{13}\text{C}$) excursion (CIE) (Kennett and Stott 1991; Koch *et al.* 1992; Thomas *et al.* 2002; Pagani *et al.* 2006), generally accepted to reflect the geologically rapid injection of ^{13}C -depleted carbon, in the form of CO_2 and/or CH_4 , into the global exogenic carbon pool (Fig. 1).

The apparent conjunction between carbon input and warming has fuelled the hypothesis that increased greenhouse gas concentrations resulted in greenhouse warming during the PETM. The total amount of carbon input during the PETM, which is known to within an order of magnitude (Dickens *et al.* 1997; Zachos *et al.* 2005; Pagani *et al.* 2006), was about 4-8 times the anthropogenic carbon release from the start of the industrial era up to today (Marland *et al.* 2005), and comparable to that expected from gross anthropogenic emissions through the end of the 21st century (Intergovernmental-Panel-on-Climate-Change 2001). In association with carbon cycle and climatic change the PETM also stands out as a time of major biotic restructuring. Given the probable ties between releases of near-modern levels of carbon-based greenhouse gases and PETM climatic and biotic change, the PETM has developed as a provocative geological case study in global change, and many of the event's characteristics and mechanisms are under intensive study. A large volume of research on the PETM has appeared over the past decade (Fig. 2), and in this paper we aim to review and synthesize this material, including the duration and magnitude of carbon cycle perturbation, magnitude of warming, changes in ocean chemistry and marine and terrestrial biotic response.

The age of the PETM

Initially, the PETM was placed within the latest Palaeocene (Berggren *et al.* 1995) and as such termed the Late Palaeocene Thermal Maximum (LPTM) (Zachos *et al.* 1993; see papers in Knox *et al.* 1996, and in Aubry *et al.* 1998). In 2000, the Palaeocene – Eocene (P/E) boundary global stratotype section and point (GSSP) was formally defined at the base of the clay layer coinciding with the steepest slope of the negative CIE (Aubry and Ouda 2003; Gradstein *et al.* 2004) in the Gabal Dababiya section (Egypt). As a consequence, the base of

the CIE has been used as global reference to pinpoint the P/E boundary. In a few publications the term Initial Eocene Thermal Maximum (IETM) has been used because the maximum absolute temperatures occurred after the Palaeocene – Eocene boundary (see Wing *et al.* 2003; Zachos *et al.* 2003; Bowen *et al.* 2004). We will use the term PETM throughout this paper.

In the marine realm, the PETM is approximately coeval with the short planktonic foraminiferal zone E1, of which the base coincides with the Palaeocene – Eocene boundary (Pearson and Berggren 2005). The PETM is located within calcareous nannoplankton zone NP9 (Martini 1971) and CP8 (Okada and Bukry 1980), and its base occurs close to the benthic foraminiferal extinction (BFE) event (Fig. 1) (Thomas and Shackleton 1996). In the North Sea, the CIE and its recovery cover the dinoflagellate cyst (dinocyst) zone *Apectodinium angustum* (Powell *et al.* 1996; Sluijs 2006) and coincide with the interval without foraminifera (planktic and benthic, including agglutinated forms), with large pyritized diatoms (see e.g., Gradstein *et al.* 1994; van Eetvelde and Dupuis 2004). In the terrestrial realm, the base of the CIE coincides with the Clarkforkian - Wasatchian North American Land Mammal Age (NALMA) zone boundary, and is correlative or nearly so (within 10's to 100's of kyr) with the Gashatan – Bumbanian land mammal age boundary in Asia and the Cernaysian – Neustrian European land mammal age boundary (Hooker 1998). The CIE occurs within radiolaria zone RP7 in the low latitudes, but marks the RP6-7 boundary in the South Pacific (Gradstein *et al.* 2004). Considering the uncertainties in radiometric dating and orbital tuning, the PETM occurred between 55.8 and 55.0 Ma ago (Berggren *et al.* 1992; Norris and Röhl 1999; Röhl *et al.* 2003; Gradstein *et al.* 2004; Lourens *et al.* 2005; Westerhold *et al.* in press).

The carbon isotope excursion

The negative CIE has been shown to be a distinctive, globally identifiable geochemical marker for the PETM in marine and continental sedimentary rocks (Fig. 1) (e.g., Kennett and Stott 1991; Koch *et al.* 1992; Stott *et al.* 1996). The CIE is considered to reflect the injection and subsequent removal of huge amounts of ¹³C-depleted carbon into the ocean-atmosphere system (Dickens *et al.* 1995; Dickens 2001a).

Shape

Details of the rate and timing of $\delta^{13}\text{C}$ change in the oceans, atmosphere, and continental reservoirs, which we will refer to as characterizing the ‘shape’ of the CIE, are needed for $\delta^{13}\text{C}$ curves to serve as a tool for correlation of PETM sections and to provide information on the dynamics of carbon release and sequestration during the event (Dickens *et al.* 1997; Dickens 2001a). Defining the detailed shape of the CIE is complicated, however, in that the temporal evolution of $\delta^{13}\text{C}$ values through the PETM may be different for various substrates and environments and may also be obscured by short-term changes in sedimentation rates that are difficult to recognize (Bowen *et al.* 2006) (see discussion below).

Following attempts to account for accumulation rate changes in deep marine sections affected by carbonate dissolution, a fairly consistent picture of the general shape of the CIE has emerged from terrestrial and marine environments (Bowen *et al.* 2006) (Fig. 1). The initiation of the CIE is marked by an abrupt, negative shift in $\delta^{13}\text{C}$ values, occurring within several hundreds or thousands of years. This is followed by a phase of relatively stable, low values, which has been termed the ‘body’ of the CIE, and a subsequent recovery to higher $\delta^{13}\text{C}$ values that follows an exponential trend. The general shape of the CIE has been interpreted to reflect a potentially pulsed geologically rapid input of ^{13}C -depleted carbon into the system, followed by gradual sequestration of the excess carbon through burial in rocks (e.g., Dickens *et al.* 1997; Zachos *et al.* 2005). The existence of a $\delta^{13}\text{C}$ plateau during the body of the CIE may reflect a lag between carbon release and the onset of net sequestration (Bowen *et al.* 2006), but the exact duration of this lag and mechanisms causing it remain unclear.

For both marine and continental records, several uncertainties affect estimation of the pace and duration of carbon release, which is relevant to constraining the source of carbon and modelling the effect of carbon input on ocean carbonate chemistry (Dickens *et al.* 1997; Schmidt and Schindell 2003; Cramer and Kent 2005). The $\delta^{13}\text{C}$ records based on different foraminifer species and/or size fractions of the intensively studied Ocean Drilling Program (ODP) Site 690 (Maud Rise, Weddell Sea) indicate several cm of stratigraphic offset for the onset of the CIE (Fig. 1; see also Thomas 2003). In the $\delta^{13}\text{C}$ records from continental sections in the Bighorn Basin (Wyoming, United States of America), the CIE onset as marked by soil nodule carbonate and dispersed

organic carbon (DOC) is offset by several meters. several hypotheses have been proposed to explain stratigraphic offsets in marine carbonate records, including lags in the propagation of injected carbon from the atmosphere to the surface and deep oceans, local changes in productivity, and post-depositional mechanisms (such as diagenesis and differential bioturbation; (e.g., Thomas *et al.* 2002; Thomas 2003; Stoll 2005). Lags in the Bighorn Basin organic carbon $\delta^{13}\text{C}$ records have been hypothesized to reflect enhanced downward diffusion of atmospheric CO_2 with subsurface diagenesis in an environment of good drainage and elevated temperature and $p\text{CO}_2$ (Magioncalda *et al.* 2004) or the detrital origin of DOC in these sections (Bowen, unpublished).

Substrate-specific differences also exist in the shape of the body of the CIE. In the Bighorn Basin soil nodule $\delta^{13}\text{C}$ record and the *Subbotina* and *Acarinina* records of ODP Site 690, the body is characterized by relatively stable $\delta^{13}\text{C}$ values with a gentle trend towards higher values. Minimum $\delta^{13}\text{C}$ values in these records are thus located at the base of the body of the CIE. However, minimum bulk $\delta^{13}\text{C}$ values occur ~50 cm higher.

One aspect of the CIE shape that has been invoked as evidence of PETM carbon cycle dynamics is a multi-stepped drop in $\delta^{13}\text{C}$ values during the onset of the CIE in several relatively complete bulk carbonate records (Bains *et al.* 1999; Zachos *et al.* 2005) (Fig. 1), which has been interpreted as evidence for multiple injections of carbon (Bains *et al.* 1999; Bains *et al.* 2003). The soil nodule record from the Bighorn Basin also appear to record a short plateau during the onset of the CIE, perhaps representing a few thousand years of relative $\delta^{13}\text{C}$ stasis (Fig. 1) (Bowen *et al.* 2001; Bowen *et al.* 2006). While the plateau also appeared in the 3-5 μm size fraction - which is dominated by the calcareous nannofossil species *Toweius* (Stoll 2005) - at Site 690, it has not been reproduced in single foraminifer $\delta^{13}\text{C}$ records (Fig. 1) (e.g., Thomas *et al.* 2002), which consistently lack intermediate values. Resolving the pattern - whether pulsed or unique - of carbon release at the onset of the PETM remains a central challenge to understanding carbon cycle perturbation during the PETM.

Above differences must reflect factors other than the $\delta^{13}\text{C}$ evolution of the exogenic carbon pool, such as dissolution, local productivity and vital effects, and complicate attempts to correlate PETM sections based on

the details of carbon isotope curves (e.g., Bains *et al.* 1999). As additional data is gathered, these discrepancies may reveal more detailed information on PETM carbon cycle dynamics within the study systems.

During the recovery phase, $\delta^{13}\text{C}$ values rise from values characteristic of the CIE body, but remain lower than pre-CIE values. This shift from pre-PETM to post-PETM values is in pace with a longer-term decline in exogenic $\delta^{13}\text{C}$ values during the Palaeocene – early Eocene (Zachos *et al.* 2001), suggesting a remarkable decoupling of the mechanisms underlying the transient carbon cycle changes of the PETM and the longer-term evolution of the early Palaeogene carbon cycle. The stratigraphic thickness of the recovery phase relative to the thickness of the body of the CIE is larger in at least some of the marine records than in the terrestrial realm. This can be explained, at least in part, by strong variations in deep marine sedimentation rates due to the fluctuations in the depths of the lysocline and CCD (Zachos *et al.* 2005), and possible changes in production rate of calcite (Kelly *et al.* 2005). As improved high-resolution age models and estimates of accumulation rate changes are developed, a consensus should emerge regarding the pace of carbon input and sequestration during the recovery phase and more accurate correlation based on the shape of the CIE should be possible.

Magnitude

The maximum magnitude of the CIE varies greatly between various records, indicating that the manifestation of the CIE at any single site and substrate reflects both changes in the global exogenic $\delta^{13}\text{C}$ budget and local or substrate-specific effects. Separation of local and global effects is therefore necessary in order to understand the ‘true’ global magnitude of the CIE, and could additionally allow $\delta^{13}\text{C}$ records to be interpreted in terms of local environmental or biotic change. Because the CIE magnitude remains a primary form of evidence for the size of the PETM carbon release, and a 1‰ difference in the global CIE magnitude could alter release estimates by 1000 Gt or more, this issue is critical to accurate understanding of PETM carbon cycle forcing.

Planktonic foraminifera show a 2.5- >4‰ excursion with a high level of variability among sites and taxa; e.g., at Site 690 up to 4‰ in the mixed layer dweller *Acarinina*, 2-3‰ in the mixed layer dweller *Morozovella* and 2‰ in thermocline dweller *Subbotina* (e.g., Thomas and Shackleton 1996; Thomas *et al.* 2002; Zachos *et al.* 2003; Tripathi and Elderfield 2004; Cramer and Kent 2005). In contrast, only a ~2‰ CIE is recorded in isolated calcareous nannofossils at Site 690 (Stoll 2005). A large $\delta^{13}\text{C}$ offset between planktonic data has also been reported from the Kerguelen Plateau (Southern Indian Ocean) (Lu and Keller 1993), whereas a lesser offset was noted in the Bay of Biscay (Pardo *et al.* 1997) although this may be associated to the relatively low resolution of this study. The average magnitude of the CIE based on benthic foraminifera is ~2.5‰ (e.g., (Kennett and Stott 1991; Thomas and Shackleton 1996; Zachos *et al.* 2001; Nunes and Norris 2006); Fig. 1), although considerable variation is observed between different benthic foraminiferal species and locations. The CIE in soil carbonate nodules is 5-6‰ (Koch *et al.* 1992; Bowen *et al.* 2001; Bowen *et al.* 2002; Bowen *et al.* 2004) and it is 4-5‰ in terrestrial higher plant n-alkanes (Pagani *et al.* 2006). The magnitude recorded in total organic carbon $\delta^{13}\text{C}$ records generated in terrestrial (Magioncalda *et al.* 2004) and marine locations (e.g., Dupuis *et al.* 2003; Steurbaut *et al.* 2003; Sluijs 2006) is ~5‰.

Bowen *et al.* (2004) analyzed a number of local effects that might account for differences in the magnitude of the CIE in marine and mid-latitude terrestrial records. Changes in marine fractionation processes, such as the tendency for foraminiferal calcite to become ^{13}C -enriched with lower pH and $[\text{CO}_3^{2-}]$ (Spero *et al.* 1997), were argued to be relatively minor, explaining up to ~0.5‰ damping of the CIE in foraminiferal records (Bowen *et al.* 2004). The study attributed the larger terrestrial excursion primarily to increased carbon isotope fractionation by plants and changes in soil carbon cycling rates due to increased relative humidity and soil moisture during the body of the PETM. The CIE magnitude in biomarkers (C29 n-alkanes) records from high northern latitudes are consistent with the Bowen *et al.* (2004) analysis, but it has been argued that water-cycle induced changes in plant and soil carbon balance would be minimal given the relatively wet, cool climate of the early Palaeogene Arctic (Pagani *et al.* 2006). In addition, new evidence from Bighorn Basin fossil floras may indicate drier, rather than wetter, mid-latitude PETM climate (Wing *et al.* 2005). The implications of magnitude differences among various CIE records and the magnitude of the ‘global’ excursion therefore remain unclear.

Among the terrestrial records, both the biomarker and palaeosol records may be affected by changes in the local composition of vegetation during the PETM. On the other hand, changes in growth rate and cell size and geometry of nanoplankton which are likely to have occurred with the environmental change recorded at the PETM, might have affected the CIE magnitude in some bulk carbonate and nannofossil-specific isotope records (e.g., Popp *et al.* 1998; Bralower *et al.* 2004).

Nunes and Norris (2006) suggested that variations in CIE magnitude among benthic $\delta^{13}\text{C}$ records from multiple sites reflect changes in deep oceanic circulation. However, the benthic isotope records comprise mostly multi-specimen records which could be influenced by bioturbation (evidenced by single specimen planktonic foraminifer isotope data within the PETM of for example Site 690, Fig. 1; Thomas *et al.* 2002) causing mixing between pre-CIE and CIE values. Moreover, some sites have suffered severe dissolution, while at other sites only very small benthic foraminifera are present within the body of the CIE implying that these records are incomplete (see Thomas *et al.* 2000 for a record from Site 690 where the species *Nuttallides truempyi* is absent during the peak PETM). In addition, deep water $\delta^{13}\text{C}$ gradients were very small during the early Eocene warm period, making reconstructions of deep-water circulation difficult (Sexton *et al.* 2006).

Duration and age models

Age models for the PETM and/or CIE generally agree that the whole event took 100 to 250 kyr, although none of the various approaches revealed consistent estimates for the total duration as well as the duration of its different phases (Fig. 1). These differences may be partly explained by uncertainties in the detailed ‘shape’ of the CIE itself, as discussed above. Here, we will discuss and update previously published age models.

An estimate for the duration of the PETM in the terrestrial realm was derived from the Polecat Bench section in the Bighorn Basin, based on the relative stratigraphic thickness of the CIE compared to that of Chron C24r, and the 2.557myr estimate for the duration of this chron by Cande and Kent (1995). Sedimentation rates in the Bighorn Basin depend largely on the accommodation space resulting from the apparently constant subsidence (Wing *et al.* 2000). Bowen *et al.* (2001) found a ~40m stratigraphic thickness for the body of the CIE and ~15m for the recovery based on the soil nodule $\delta^{13}\text{C}$ record (Fig. 1), implying a

~55m thickness for the total CIE. Applying the average sedimentation rates of 47.5cm per kyr for Chron C24r (Gingerich 2000), based on the magnetostratigraphic results of Butler et al. (1981), results in a ~84kyr duration for the body of the CIE (Bowen *et al.* 2001) (Fig. 1). More recently, Koch et al. (2003) updated the magnetostratigraphy, and showed that ~1030m of sediment accumulated during C24r, which would result in average sedimentation rates of 40.2cm.kyr⁻¹, implying a ~71kyr duration for the body of the CIE.

Recent studies on astronomically-derived cycles in lowermost Palaeogene successions from ODP Leg 208 on the Walvis Ridge (Lourens *et al.* 2005) has confirmed interpretations from previous studies (e.g., Röhl *et al.* 2003) that much more time is represented in the interval between the CIE and the C24r/24n reversal than estimated by Cande and Kent (Cande and Kent 1995), and that the duration of Chron 24r was in the order of 3.118myr (Westerhold *et al.* in press). This implies that average sedimentation rates in the Bighorn Basin during C24r were approximately 33.0cm.kyr⁻¹ (i.e., 1030m/3.118myr), significantly lower than previous estimates, resulting in an estimate of the duration of the body of the CIE at Polecat Bench of ~120kyr (i.e., 40m/33.0cm.kyr⁻¹) and at least ~170kyr (i.e., 55m/33.0cm.kyr⁻¹) for the entire PETM.

Two commonly used age models were derived from the relatively expanded marine PETM section at ODP Site 690. Both age models agree across the main body of the CIE, but differ significantly for the duration of the recovery phase. The first of these (Röhl *et al.* 2000) was based on core-scan X-Ray Fluorescence (XRF) Fe and Ca measurements through the CIE, and recognition of precession cycles (duration ~ 20kyr) in these records. The authors counted 4 cycles within the body of the CIE, and another 7 within the recovery phase, recognized by the location of inflection points of the bulk carbonate $\delta^{13}\text{C}$ record, thus arriving at an estimate for the entire CIE of 210 to 220kyr. The second of these models is based on the extraterrestrial He (³He_{ET}) concentrations of the Site 690 PETM sediments and the assumption that the flux of this isotope to the Earth remained constant during the PETM (Farley and Eltgroth 2003). The background absolute flux of ³He_{ET} to the sea floor during the PETM was estimated from the ³He_{ET} concentration in 13 samples taken from C24r and C25n above and below the PETM and average sedimentation rates obtained from Aubry et al. (1996). These average sedimentation rates were based on a relatively low resolution magnetostratigraphy (Spiess 1990) - which has since been revised by Ali et al. (2000), -and durations for C24r and C25n of 2.557

and 1.650 myr (Cande and Kent 1995), respectively. Accordingly, Farley and Eltgorth (2003) arrived at an estimate of ~ 90 kyr for the duration of the body of the CIE and ~ 120 for the entire PETM.

The $^3\text{He}_{\text{ET}}$ -based age model is subject to several important uncertainties. First, the depth level of the reversal between C24r and C24n has not been clearly identified at Site 690, being adjacent to an unconformity. The carbon isotope excursion associated with Eocene Thermal Maximum 2 (ETM2), which is ~ 150 kyr older than this reversal (Cramer *et al.* 2003; Lourens *et al.* 2005; Westerhold *et al.* in press), is present at Site 690 (Cramer *et al.* 2003; Lourens *et al.* 2005) and could thus be used as an alternate calibration point. Second, Chron C24r was likely 561 kyr longer than assumed (Westerhold *et al.* in press). Third, ODP Site 690 recovered the upper Palaeocene and lower Eocene in a single hole only, but we know from multiple-hole drilling that sediment cores expand when they are released from the overlying load, so that part of the core is lost. The average expansion factor for Sites 1262-1267 at Walvis Ridge, for instance, varied between 110 and 118% (Zachos *et al.* 2004), which implies recovery gaps of 1 to 1.8m between each core, similar to the value of 1.2-1.8 m found by Florindo and Roberts (2005) for the double-cored, younger part of Site 690. This core loss due to expansion has not been accounted for in Site 690 studies, but the whole CIE is within one core at Site 690, so that cycle counts limited to this interval are not affected (Röhl *et al.* 2000). Fourth, the 13 samples used to calculate the background $^3\text{He}_{\text{ET}}$ flux may be affected by temporal (possibly orbitally-forced) variations in sedimentation rates, probably as covered by the ‘minimum’ and ‘maximum’ estimates based on the standard errors in the background flux values, which vary between 0.38 and 0.97 pcc.cm⁻².kyr⁻¹ (1 pcc = 10⁻¹² cm³ of He at STP). Fifth, $^3\text{He}_{\text{ET}}$ fluxes may not have been constant during C24r and C25n (Mukhopadhyay *et al.* 2001; Kent *et al.* 2003), and are known to vary by an order of magnitude over millions of years (Farley 2001). Background flux values appear significantly higher during C24r than during C25 (Table 1c).

In order to re-evaluate the He-based age model and test its sensitivity to the above uncertainties, we calculated several age models for the PETM using different assumptions and corrections for the above issues (Table 1, Fig. 3). We adopt durations of C25n (504kyr) and the interval between the onset of C24r and the ETM2 (2940kyr) from Westerhold *et al.* (in press) and apply different sediment expansion factors. Because background $^3\text{He}_{\text{ET}}$ content/g sediment is quite sensitive to small changes in these assumptions is large the

resulting estimates for the total duration of the PETM vary between 90 ± 10 and 140 ± 30 kyr for the most likely scenarios (Fig. 3). Regardless of the assumptions, however, the helium model requires a very large increase in sedimentation rate towards the end of the PETM, thus giving a rapid recovery period relative to the body of the PETM (Fig. 3) (Farley and Eltgroth 2003).

A rapid recovery may be supported by the theory that calcite production in the photic zone increased during the recovery phase (Kelly *et al.* 2005) or calcite preservation increased due to the ‘overshoot’ of the lysocline following silicate weathering (Dickens *et al.* 1997; Zachos *et al.* 2005). The $^3\text{He}_{\text{ET}}$ and cyclostratigraphic age models each provide estimates of the magnitude of sedimentation rate increases due to these mechanisms. Our re-calculated He-based estimates suggest a duration of 30 to 35 kyr for the recovery phase. Röhl *et al.* (2000) counted 7 precession cycles through the recovery interval at ODP Site 690, implying a relatively prolonged, ~ 140 kyr, recovery and negligible changes in sediment accumulation rates. Clear identification of cycles in this interval of the 690 cores is complicated, however, by the high carbonate content of the sediments. A cyclostratigraphic study on an Italian PETM section (Giusberti *et al.* in press) counted only 5 precession cycles (i.e., ~ 100 kyr) within the recovery interval. Direct site-to-site correlation of the termination of the CIE is complicated, however, due to the lack of a clear $\delta^{13}\text{C}$ inflection point, which makes the definition of this level somewhat subjective. These differences demonstrate that significant uncertainty remains regarding the pace of carbon cycle recovery from the PETM. Studies in progress, including cycle and $^3\text{He}_{\text{ET}}$ studies will likely provide better constraints regarding the durations of the various parts of the CIE.

The temperature anomaly

Deep sea benthic foraminiferal calcite consistently shows a $>1\text{‰}$ negative excursion in $\delta^{18}\text{O}$ (e.g., (Kennett and Stott 1991; Bralower *et al.* 1995; Thomas and Shackleton 1996; Zachos *et al.* 2001) during the PETM (see above for $\delta^{13}\text{C}$). Application of empirical temperature- $\delta^{18}\text{O}$ relations (e.g., Shackleton 1967; Erez and Luz 1983) indicates a deepwater temperature rise of $\sim 4\text{--}5^\circ\text{C}$, which is corroborated by benthic foraminifer Mg/Ca values (Tripathi and Elderfield 2005). This warming was first interpreted to reflect a shift in deep water formation from high to low latitudes (Kennett and Stott 1991). Evidence accumulating since then indicates

that the dominant source of intermediate and deep water formation likely remained at high latitudes, although it may have switched from southern to northern high latitudes (Pak and Miller 1992; Bice and Marotzke 2001; Thomas 2004; Tripathi and Elderfield 2005; Nunes and Norris 2006). Although some component of deep water warming could reflect different temperatures at northern and southern hemisphere sites of deep water formation, it is likely that most of the $\sim 5^{\circ}\text{C}$ warming was the result of surface water warming in sub-polar regions (Tripathi and Elderfield 2005).

Planktonic foraminiferal $\delta^{18}\text{O}$ and Mg/Ca excursions generally point towards $\sim 5^{\circ}\text{C}$ surface water warming over a large range of latitudes (Kennett and Stott 1991; Thomas and Shackleton 1996; Charisi and Schmitz 1998; Thomas *et al.* 2002; Zachos *et al.* 2003; Tripathi and Elderfield 2004). At Site 690 the maximum warming appears to be as much as $6\text{--}8^{\circ}\text{C}$ (Kennett and Stott 1991; Thomas *et al.* 2002). The $\delta^{18}\text{O}$ records for the mixed-layer dweller *Acarinina* and thermocline-dweller *Subbotina* follow somewhat different trajectories through the event, with *Subbotina* recording its lowest (warmest) $\delta^{18}\text{O}$ values at the base of the CIE-body and *Acarinina* reaching its $\delta^{18}\text{O}$ minimum halfway through the CIE-body (~ 171 mbsf). The apparent decoupling between thermocline and surface water temperatures at Site 690 seems also to be reflected in Mg/Ca-based temperature reconstructions from subtropical Pacific Site 1209 (Zachos *et al.* 2003). At Site 690, and perhaps to a lesser degree at Site 1209, it is accompanied by a sudden increase in $\delta^{13}\text{C}$ values of *Acarinina*, suggesting the possible influence of surface water stratification and productivity on temperature and carbon isotope values.

A salinity-independent organic palaeothermometer TEX_{86} ' record across a PETM succession in the Arctic Ocean revealed a warming of $\sim 5^{\circ}\text{C}$ close to the North Pole (Sluijs *et al.* 2006), implying that the magnitude of temperature change in tropical and (North-) polar surface waters were equal and excluding polar amplification scenario for the PETM at least for the northern hemisphere (Tripathi and Elderfield 2005; Sluijs *et al.* 2006). The absence of sea ice, as implied by the high TEX_{86} '-derived average absolute temperatures (Sluijs *et al.* 2006), was likely a critical factor determining the lack of polar temperature change amplification.

Records from near-shore marine sediments provide evidence for greater temperature-change heterogeneity in coastal settings. A benthic foraminiferal $\delta^{18}\text{O}$ record from the neritic sediments recovered at

Bass River, New Jersey (USA), exhibits a relatively large excursion that, assuming no change in salinity, suggests 8° of PETM warming (Cramer *et al.* 1999). This finding has recently been supported by the salinity-independent TEX₈₆ record from the nearby Wilson Lake borehole (New Jersey) (Zachos *et al.* 2006). In contrast, a benthic foraminiferal $\delta^{18}\text{O}$ record from the Egyptian shelf shows a ~1‰ negative excursion (Schmitz *et al.* 1996), which might imply ~4°C of warming but hardly stands out from the background scatter. Application of salinity-independent temperature proxies at this site may help constrain the interpretation of the $\delta^{18}\text{O}$ data, but the general suggestion is that the magnitude of coastal warming may have varied by at least a factor of 2.

Warming estimates from the Bighorn Basin are also in the range of 5°C. Koch *et al.* (2003) and Bowen *et al.* (2001) calculate a 3-7°C warming based on carbonate soil nodule $\delta^{18}\text{O}$. Fricke and colleagues (Fricke *et al.* 1998; Fricke and Wing 2004) infer that PETM mean annual temperature was 4-6°C warmer than before and after the PETM, based on $\delta^{18}\text{O}$ of biogenic phosphate. Estimates from leaf margin analysis of fossil leaves are consistent with these other data, implying a ~5°C rise in mean annual temperature during the PETM (Wing *et al.* 2005).

Acidification of the ocean

According to theory, and as observed and expected in the present and future ocean (Caldeira and Wickett 2003; Feely *et al.* 2004; Delille *et al.* 2005; Orr *et al.* 2005; Kleypas *et al.* 2006), the instantaneous induction of large amounts of CO₂ or CH₄ (which would rapidly be oxidized to CO₂ in the atmosphere) into the ocean-atmosphere system at the PETM should have increased the carbonic acid (H₂CO₃) concentration in the oceans. This acidification would reduce the depth of the calcite compensation depth (CCD) and lysocline in the oceans, leading to seafloor carbonate dissolution and reduced carbonate burial, which would restore the pH balance in deep ocean waters over 10³ to 10⁴ year timescales (Dickens *et al.* 1997; Dickens 2000). The extent of globally averaged CCD shoaling is related to the amount of CO₂ injected into the ocean-atmosphere system, and thus may be used to constrain the amount of carbon (Dickens *et al.* 1997).

Seafloor carbonate dissolution during the PETM has been documented in sediments across a ~2km depth transect (palaeodepths ~ 1500-3600 m) at Walvis Ridge in the southeast Atlantic Ocean (Zachos *et al.* 2005). These data allow estimation of PETM carbon release as at least ~4,500 Gt if it is assumed that the magnitude of shoaling at Walvis Ridge was characteristic of the global ocean, that the geometry of the ocean basins and seawater alkalinity were equal to those of the modern ocean, and that the release rates of carbon compounds were comparable to projected rates of anthropogenic emissions. It is unlikely that any of these assumptions is strictly correct, and therefore the estimated carbon release can only be taken as a rough estimate that is broadly consistent with, but perhaps suggests a somewhat larger release than, previous estimates (e.g., (Dickens *et al.* 1995). In particular, it is not clear that the dramatic shoaling of the CCD at Walvis Ridge was characteristic of the world oceans (e.g., Thomas 1998). Carbonate content at Site 690 (palaeodepth ~ 1900 m), only decreased from ~85% to ~60% (e.g., Bralower *et al.* 2004). At central Pacific Site 1209 (Shatsky Rise), which was deeper than the shallowest Walvis Ridge site, carbonate content decreased by only ~ 10% (Colosimo *et al.* 2005), and decreased carbonate content at the Mead Stream section in New Zealand (continental slope) has been interpreted to reflect dilution by increased terrigenous influx rather than dissolution (Hollis *et al.* 2005a). These data seem to mimic the general pattern of more severe dissolution in the Atlantic relative to the Pacific that has been predicted by a modelling study that assume that ocean circulation patterns in the late Palaeocene were analogous to those of present day (Dickens *et al.* 1997), but the magnitude of lysocline and CCD shoaling at Walvis Ridge was much larger than predicted in that study. Severe dissolution has also been observed in many marginal basins, such as the North Sea region (e.g., Gradstein *et al.* 1994), and the marginal Tethys, (e.g., Ortiz 1995; Speijer *et al.* 1997; Speijer and Wagner 2002; Dupuis *et al.* 2003; Schmitz *et al.* 2004; Ernst *et al.* 2006). Understanding the controls on dissolution at these sites, including local factors such as carbonate and organic matter production rates, clastic influx, and post-burial dissolution, as well as large-scale factors such as ocean circulation, will be critical to extrapolating to derive a global estimate of ocean acidification and robust estimates of the magnitude of carbon release during the PETM.

The recovery of the oceanic carbonate system may have occurred through increased rates of marine or terrestrial organic carbon burial (Bains *et al.* 2000; Beerling 2000) and through a feedback involving increased

marine carbonate carbon burial driven by silicate weathering (Dickens *et al.* 1997; Kelly *et al.* 2005). At Walvis Ridge, the lysocline deepened below pre-PETM levels during the recovery phase, suggesting elevated deepwater alkalinity and supporting the hypothesis of feedback through silicate weathering (Zachos *et al.* 2005). Marine organic-rich PETM successions have been recorded from shallow marine sections from the Tethyan margins (e.g., Bolle *et al.* 2000; Speijer and Wagner 2002; Gavrilov *et al.* 2003), the North Sea (e.g., Bujak and Brinkhuis 1998) and the Arctic Ocean (Sluijs *et al.* 2006). Despite these organic-rich deposits, and although abundant Palaeocene and early Eocene peat and coal deposits exist on the continents (e.g., Collinson *et al.* 2003; Kurtz *et al.* 2003), it is not clear to which extent (if at all) the rate of organic carbon deposition and burial increased during the PETM (e.g., Bowen *et al.* 2004).

Biotic Response

Patterns of benthic turnover

The PETM stands out in the geological record as one of the largest extinctions in deep marine calcareous benthic foraminifera, when 35-50% of the deep-sea species rapidly became extinct (Tjalsma and Lohmann 1983; Thomas 1989; Pak and Miller 1992; Thomas and Shackleton 1996; Thomas 1998, 2003). Benthic foraminifer extinction (BFE) events of this magnitude are rare in the geological record and deep-sea turnover usually takes millions of years (Thomas in press). Rapid extinction in the deep-sea is expected to be rare: many species are cosmopolitan, and are rapid colonizers. Extinction of a large fraction of deep-sea species thus requires a rapid change affecting the whole deep-ocean, the largest habitat on earth. Discussion of the cause of the extinction has concentrated on food availability, acidification, bottom water oxygen depletion and temperature, based on the palaeoecological interpretation of post-BFE assemblages, which are unfortunately not straightforward (Thomas 1998, 2003).

Food availability in the present oceans depends on surface ocean production and export production of organic matter. Deep sea benthic foraminiferal assemblages do not indicate a global increase or decrease in the food supply during the PETM (e.g., Thomas 1998). In the central Pacific (ODP Site 865) and Southern Ocean (Site 690), benthic foraminifer assemblages point to an increase in food supply, whereas the opposite is found

at Atlantic and Indian Ocean sites (Thomas 2003). Nannofossil assemblages (see below) suggest a decrease in surface productivity at Sites 690 and 865, whereas benthic foraminiferal assemblages suggest an increased food supply to the sea-floor. To explain this discrepancy, Thomas (2003) speculated that during the PETM there may have been a chemosynthetic food source at the ocean floor or that export production was more efficient, possibly because lower oxygen levels caused lower organic matter decomposition. If the latter is true, decreased oxygen concentrations of the deep ocean due to higher temperatures and possibly methane oxidation (see below) may have contributed to the BFE (Thomas 1998; Dickens 2000; Thomas 2003). Nevertheless, there is no geochemical or sedimentological evidence for severe low oxygen conditions in open ocean (Thomas in press). Small thin-walled benthic foraminifera (as well as ostracodes) in the interval just above the BFE, are associated with increased calcite corrosiveness of deep waters, which would have been detrimental to calcifiers and could have provided a selective force driving extinction (Steineck and Thomas 1996; Thomas 1998; Orr *et al.* 2005; Zachos *et al.* 2005). Extinctions, however, occurred also among non-calcifying deep marine agglutinated foraminifera (Kaminski *et al.* 1996; Galeotti *et al.* 2005). There is thus no evidence that deep-water oxygen depletion, carbonate dissolution, or increased or decreased food supply to the deep-sea were global. Therefore, the global deep ocean temperature increase, which would have raised metabolic rates and lead to ecosystem restructuring, may have been the most important cause of the BFE (Thomas in press).

Benthic foraminifer studies on neritic and upper bathyal assemblages are largely restricted to the Tethyan basin and the Atlantic margins. Extinction and temporal changes in composition in these settings were less severe than in the deep sea (Gibson *et al.* 1993; Speijer and Schmitz 1998; Thomas 1998; Cramer *et al.* 1999; Speijer and Wagner 2002). Speijer and colleagues argue that late Palaeocene through early Eocene assemblages generally indicate relatively oligotrophic conditions along the southern Tethyan margin, but show a transient increase in food supply during the PETM (Speijer and Schmitz 1998; Speijer and Wagner 2002; Scheibner *et al.* 2005), consistent with multi-proxy evidence from neritic realms around the world (see sections on dinocysts and nannofossils).

Larger foraminifera show a large turnover in the Tethyan realm, which has long been recognized but only recently correlated to the PETM (Pujalte *et al.* 2003). This turnover is characterized by a decrease in generic diversity, but the few genera that became dominant during the PETM show rapid diversification on the species level, possibly due to migration from a previously isolated basin or fast specialization as a result of changing environments (Pujalte *et al.* 2003).

Unlike benthic foraminifera, the PETM does not stand out as a major extinction event in the deep sea ostracode fossil record (Boomer and Whatley 1995), but it has not been well studied at high resolution. The only reasonable-resolution record from the deep sea is by Steineck and Thomas (1996) on assemblages from Site 689, close to Site 690 but ~ 900 m shallower. Their results indicate that ostracodes were smaller and more thin-walled during the PETM, suggesting that within-lineage changes in ostracode morphology may reflect calcite corrosivity.

Tethyan neritic ostracode assemblages on the other hand, show a turnover at the PETM (Speijer and Morsi 2002, and references therein), when long-ranging Palaeocene taxa were outcompeted by a species that is thought to thrive in upwelling areas. Hence, the dominance of this species is interpreted as a response to enhanced food supply and decreased bottom water oxygenation (Speijer and Morsi 2002). These Tethyan assemblages suggest a sea level rise at the PETM, an interpretation consistent with information from other shallow marine successions (Powell *et al.* 1996; Cramer *et al.* 1999; Oreshkina and Oberhänsli 2003; Crouch and Brinkhuis 2005; Sluijs *et al.* 2006).

Migration and radiation patterns in the planktonic realm

The most dramatic planktonic microfossil signature at the PETM is recorded in organic-walled dinoflagellate cysts (dinocysts). Most organic cyst-forming dinoflagellates have life strategies that require a restricted water depth and are, hence, specialized in neritic settings (Fensome *et al.* 1996). They are very sensitive to changes in the physiochemical characteristics of the surface waters, including salinity, temperature, nutrient availability and stratification (Sluijs *et al.* 2005). The taxon *Apectodinium* originated close to the Danian-Selandian boundary (Brinkhuis *et al.* 1994; Guasti *et al.* 2005), and abundant occurrences remained largely

restricted to low latitudes throughout the Palaeocene (Bujak and Brinkhuis 1998). In contrast, every studied dinocyst-bearing succession across the PETM has yielded abundant *Apectodinium*, usually >40% of the dinocyst assemblage (Heilmann-Clausen 1985; Bujak and Brinkhuis 1998; Heilmann-Clausen and Egger 2000; Crouch *et al.* 2001; Sluijs *et al.* 2005; Sluijs *et al.* 2006) (Fig. 4). Such a global, synchronous acme is unique in the dinocyst fossil record, which spans the late Triassic to the Recent. During the PETM temperate to polar sea surface temperatures increased to allow poleward migration of *Apectodinium* (Bujak and Brinkhuis 1998; Crouch *et al.* 2001; Sluijs *et al.* 2006). The *Apectodinium* acme appears to be associated not only with high temperatures, but also with a strong increase in nutrient availability in marginal marine settings (Powell *et al.* 1996; Crouch *et al.* 2001; Crouch *et al.* 2003a; Crouch and Brinkhuis 2005): the motile dinoflagellates that formed *Apectodinium* cysts were likely heterotrophic and fed on organic detritus or other plankton (Bujak and Brinkhuis 1998). Increased nutrient input by rivers is consistent with results from fully coupled general circulation models predicting an intensified hydrological cycle at elevated greenhouse gas concentrations (Pierrehumbert 2002; Huber *et al.* 2003; Caballero and Langen 2005). Other microfossil, geochemical and lithological evidence at least supports locally intensified runoff during the PETM, although several clay mineral records suggest that this started prior to the CIE (Robert and Kennett 1994; Gibson *et al.* 2000; Ravizza *et al.* 2001; Speijer and Wagner 2002; Egger *et al.* 2003; Gavrillov *et al.* 2003; Gibbs *et al.* 2006; Pagani *et al.* 2006). *Apectodinium* was likely euryhaline, i.e., tolerant to a wide range of salinities, as the acme has been recorded from the relatively fresh (Pagani *et al.* 2006; Sluijs *et al.* 2006) Arctic Ocean to the likely more salty subtropical regions and even open ocean settings (Egger *et al.* 2000). Because of this complex palaeoecology it is difficult to elucidate which environmental parameter(s) was the driving force behind the global *Apectodinium* acme during the PETM.

Marine dinoflagellate assemblages usually show a strong proximal-distal signal, so that dinocyst assemblages can be used to reconstruct the influence of inshore waters in a more offshore locality (Brinkhuis 1994; Pross and Brinkhuis 2005; Sluijs *et al.* 2005). Dinocyst assemblages show a trend towards more offshore surface water conditions at many locations during the PETM (Crouch and Brinkhuis 2005; Sluijs *et al.* 2005) implying that eustatic transgression took place (Sluijs 2006). Although the magnitude of this transgression is

unclear, qualitatively it may be expected during a time of significant global warming because of thermal expansion and potential cryosphere melting, which together potentially comprised in the order of ~10-20m across the PETM (Miller *et al.* 2005). Furthermore, it is consistent with data on shallow marine benthic foraminifer, ostracode and grain size information (Gibson and Bybell 1994; Cramer *et al.* 1999; Speijer and Morsi 2002; Speijer and Wagner 2002; Sluijs 2006).

Apectodinium shows a large variation of morphotypes through this event. As for planktonic foraminifera (see below), it is hard to assess which of these dinocyst types represent true biological species, but intermediate forms occur, implying that they represent ecophenotypes. *Apectodinium* is member of the family Wetzeliellaceae, which underwent major radiation during or close to the PETM. There are few high-resolution studies of upper Palaeocene material (Heilmann-Clausen 1985; Bujak and Brinkhuis 1998; Iakovleva *et al.* 2001; Guasti *et al.* 2005), but associated genera, such as *Wilsonidium*, *Dracodinium* and *Rhombodinium* originated close to or at the PETM. Afterwards, new genera and species within the Wetzeliellaceae, including the genus *Wetzeliella*, developed, their evolution potentially related to other early Eocene global warming events such as ETM2 (Lourens *et al.* 2005) and ETM3 (Röhl *et al.* 2005).

Compared to dinocysts, planktonic foraminifera show a relatively minor response to the PETM. Poleward migrations include the only occurrence of the low latitude genus *Morozovella* in the Weddell Sea (Thomas and Shackleton 1996) just prior to and during the lower part of the CIE. Extinctions and radiations are largely absent but evidence of faunal turnover has been recorded at many locations (e.g., Lu and Keller 1993; Lu and Keller 1995; Pardo *et al.* 1997). The genera *Morozovella* and *Acarinina* developed extreme morphotypes during the PETM in tropical regions (Kelly *et al.* 1996; Kelly *et al.* 1998). The dominance of these newly developed taxa within the assemblages has been interpreted as indicative of relatively oligotrophic conditions in the open ocean due to changes in the thermal structure of the water column (Kelly *et al.* 1996). These PETM morphotypes might represent true evolutionary transitions or ecophenotypes reflecting unusual environmental conditions, such as stratification and nutrient depletion (Kelly *et al.* 1998).

Only few high-resolution calcareous nannofossil studies focused on palaeoecology through the PETM, although assemblage changes are extensively described (e.g., Backman 1986; Aubry *et al.* 1996; Raffi *et al.* 2005

and references therein; see also fig. 17 in Raffi *et al.* 2005 for geographic distribution maps of the recorded changes in the nannofossil assemblage). Neritic assemblages from the New Jersey Shelf were interpreted to reflect increased productivity during the PETM (Gibbs *et al.* 2006). Bralower (2002) argued that nannofossil assemblages at open ocean Site 690 reflect a change from abundant r-mode species (comprising opportunistic species, indicating eutrophic conditions with a well-mixed upper water column and a shallow thermocline) to abundant K-mode species (specialized species, indicating oligotrophic conditions with a stratified water column and a deep thermocline) at the onset of the CIE. This interpretation is consistent with that of nannofossil assemblage studies of open marine sites from the Indian Ocean (Tremolada and Bralower 2004), the Pacific Ocean (Gibbs *et al.* 2006) and the Tethys (Monechi *et al.* 2000), and supported by model studies (e.g., Boersma *et al.* 1998; Huber *et al.* 2003). However, it appears directly contradicted for Site 690 by observations on accumulation rates of Ba (Bains *et al.* 2000) and Sr/Ca in coccoliths (Stoll and Bains 2003): both suggest increased productivity. Both arguments are in debate: the latter by Bralower *et al.* (2004), the former by (Dickens *et al.* 2003), who suggested that dissociation of methane hydrate (see below) resulted in Ba²⁺ release into the ocean, thus elevated dissolved Ba²⁺ concentrations in the deep sea, causing improved preservation of sedimentary barite. In addition, changes in bottom water CO₃²⁻, (described above) may have had an effect on barite preservation (Schenau *et al.* 2001).

Not many upper Palaeocene to lower Eocene sections contain well preserved siliceous microfossil assemblages so the response of diatoms and radiolarians to the PETM is not well constrained. Sediment sequences that bear radiolaria commonly do not have a good record through the PETM (Sanfilippo and Nigrini 1998), and the well-preserved PETM assemblage from low latitude Blake Nose is unique (Sanfilippo and Blome 2001). At that site, the composition of the fauna shows no net, overall change during the PETM, although there is a minor increase in the number of first and last occurrences. In contrast, the influx of several low latitude taxa at the PETM is observed in New Zealand, suggesting poleward migrations (Hollis *et al.* 2005a; Hollis *et al.* 2005b; Hollis in press).

Diatom records through the PETM are also rare. ODP Site 752 in the eastern Indian Ocean recovered a diatom bearing PETM succession, but only biostratigraphical and taxonomical work has been done on this

material (Fourtanier 1991). A considerable turnover of the diatom flora at generic and species levels has been observed in sections from the epicontinental sea in Russia, including the appearance of short-lived taxa (Radionova *et al.* 2001; Oreshkina and Oberhänsli 2003). It has been suggested that these turnovers are associated to a more vigorous exchange of surface waters with the Tethys resulting from transgression (Oreshkina and Oberhänsli 2003).

Terrestrial mammals

The PETM stands out as a time of significant changes in terrestrial biota (Fig. 5). Perhaps the most dramatic and best-known of these is the abrupt introduction of 4 major taxonomic groups to terrestrial mammalian assemblages on the Northern-Hemisphere continents at or near the P-E boundary (Gervais 1877; McKenna 1983; Gingerich 1989; Krause and Maas 1990; Smith and Smith 1995; Hooker 1998). The first appearance of the ordinal-level ancestors of modern hoofed mammals (orders Artiodactyla and Perissodactyla), Euprimates (those bearing the complete set of anatomical characteristics uniting modern primates), and a now-extinct family of carnivores (Hyaenodontidae) has long been held by palaeontologists to represent the base of the Eocene in western North America and Europe (Gingerich and Clyde 2001; Gingerich 2006). Recent high-resolution stratigraphic studies demonstrated that they occur within meters of the CIE base at ~6 sites across the Holarctic continents (e.g., Koch *et al.* 1992; Koch *et al.* 1995; Cojan *et al.* 2000; Bowen *et al.* 2002; Steurbaut *et al.* 2003; Ting *et al.* 2003).

These first appearances are associated with long- and short-term (transient) changes in terrestrial mammal faunas and initiated a profound modernization of terrestrial mammal communities that were still dominated by archaic forms despite prolific diversification following the Cretaceous-Palaeogene boundary (Alroy *et al.* 2000). The new groups rapidly impacted the communities that they entered, producing significant increases in species richness, average species size, and proportional representation of herbivorous and frugivorous taxa, characteristics of community structure which persisted in early Eocene assemblages from the Bighorn Basin (Clyde and Gingerich 1998) (Fig. 5). The first appearances also provided a seed for longer-term changes in community composition and structure: in the context of longer-term changes in species diversity, the first

appearances are overshadowed by rapid post-PETM diversification within the new clades. Other impacts of the PETM on land mammals were transient, including a reduction in average individual body size among both new groups and lineages that ranged through the Palaeocene-Eocene boundary in the Bighorn Basin (Gingerich 1989; Clyde and Gingerich 1998) (Fig. 5). A significant taxonomic turnover between two groups of faunas assigned to the Bumbanian Asian land mammal age may reflect a shift from transient PETM fauna to a more stable early Eocene fauna, and be somewhat analogous to North American faunal changes at the end of the PETM (Ting *et al.* 2003), although the data are at much lower time resolution than those in the Bighorn Basin. No clear equivalent has been proposed for European faunas.

There is near-universal consensus that the abrupt first appearances in early Eocene mammal faunas represent synchronous dispersal of new taxa across Holarctica. Fossil biogeography (e.g., McKenna 1983) and recent studies documenting Arctic Ocean palaeo-salinity (Brinkhuis *et al.* 2006; Pagani *et al.* 2006; Sluijs *et al.* 2006) suggest that the Northern Hemisphere continents must have been linked at least intermittently by land bridges during the early Palaeogene, providing high-latitude corridors for faunal exchange. Warming during the PETM may have allowed mammals previously restricted to lower latitudes to access these inter-continental corridors, resulting in widespread dispersal of the new groups and homogenization of the Holarctic fauna (McKenna 1983; Krause and Maas 1990; Peters and Sloan 2000). A concomitant dispersal event affecting the Holarctic turtle fauna may reflect a similar climate-mediated mechanism (Holroyd *et al.* 2001).

This mechanism provides a compelling link between climate and PETM mammal turnover, but does not address the questions of where, when, or why the new immigrant groups originated. Two models for the origination of these groups have been proposed. Beard and colleagues have argued that the similarity between the early representatives of the new “PETM” groups and out-group taxa from the Palaeocene of Asia suggests an Asian origin, and that some primitive Asian representatives of the “new” clades may be of Palaeocene age (Beard 1998; Beard and Dawson 1999). In contrast, Gingerich has argued that rapid origination of these clades at unspecified locations in response to environmental perturbations associated with the PETM is both possible and plausible (Gingerich 2006).

This debate centres on the issue where and when the missing links between the new PETM groups and their ancestors occurred, and thus it has been difficult to test the competing ideas. The hypothesis for Asian origination, however, presents the testable prediction that the ‘new’ mammal groups were present in the Palaeocene of Asia. A combination of chemo-, magneto-, and biostratigraphic data shows that Hyainodontidae were indeed present in Asian Palaeocene faunas (Bowen *et al.* 2002; Ting *et al.* 2003; Meng *et al.* 2004; Bowen *et al.* 2005). Smith *et al.* (2006) argued for a slightly earlier appearance (by ca. 10 - 25 kry) of Primates in Asia. However, the failure to find ubiquitous support for the hypothesis of Asian origination during the Palaeocene, and recent evidence against other potential loci of Palaeocene origination such as the Indian subcontinent (Clyde *et al.* 2003), has led to renewed interest in the idea that environmental change during the PETM may have spurred the evolution of several important orders (Gingerich 2006).

Terrestrial plants

Palynological and macrofloral remains from the uppermost Palaeocene and lowermost Eocene have revealed no evidence for net long-term taxonomic turnover or long-lasting major changes in community structure associated with the PETM (Jaramillo and Dilcher 2000; Harrington and Kemp 2001; Wing and Harrington 2001; Collinson *et al.* 2003; Crouch *et al.* 2003b; Crouch and Visscher 2003; Harrington 2003; Wing *et al.* 2003; Harrington *et al.* 2004). These studies documented modest floral change across the P-E boundary, including the introduction of a small number of immigrant taxa (e.g., introduction of some European taxa to North America) and increases in the diversity of floras from the late Palaeocene to the early Eocene. Changes in terrestrial floras across the P-E boundary may have in some cases been diachronous and do not stand out as highly anomalous relative to background spatial and temporal taxonomic variation (Harrington *et al.* 2004).

Two recently discovered macrofloral collections of distinctive composition, however, show that major transient changes in the taxonomic composition of floras occurred during the PETM in the Bighorn Basin (Wing *et al.* 2005). These floras document the immigration of thermophilic taxa previously known from the southern United States and adjacent basins of the western United States, and the first appearance of the European immigrant palynospecies *Platycarya platycaryoides* later within the PETM. Many early Palaeogene plant

taxa underwent major geographic range shifts during the PETM, both within and between continents. These shifts are comparable to floral range shifts at the end of the Pleistocene: in both cases rapid and plastic reorganization of plant communities occurred in response to climatic and environmental change (Overpeck *et al.* 1992; Jackson and Overpeck 2000; Wing *et al.* 2005).

Summary of biotic response

The response of marine organisms to the PETM was heterogeneous. Benthic foraminifera comprise the only group that underwent significant extinction, potentially related to the increased temperature, although lower oxygen levels, changes in primary productivity or the biological carbon pump, and carbonate corrosivity may have played a role. Deep sea ostracode faunas may also reflect this increased corrosivity, but the geographical extent is unclear. In the surface ocean, a global acme of the (sub)tropical dinocyst *Apectodinium* occurred along the continental margins, and has been interpreted as a combination of warming and an increase in trophic level of marginal seas, as supported by neritic lithological, ostracode, benthic foraminifer and nannofossil information. Trophic changes in the open ocean are still debated: planktonic foraminiferal and nannofossil assemblages suggest that relatively oligotrophic conditions existed during the PETM, whereas increased barite accumulation rates and Sr/Ca of nannoplankton (at some sites) have been interpreted as indicative of elevated surface productivity. Benthic foraminifera suggest an increase in food supply to the sea floor at some (but not all) open ocean locations, but not necessarily higher surface productivity. Both dinocysts and neritic ostracodes indicate that eustatic sea level rose during the PETM. Finally, extreme morphotypes of several planktic protist microfossil groups are restricted to the PETM and probably represent ecophenotypes.

The terrestrial biotic record of the PETM demonstrates that climate change induces changes in the geographic distribution of terrestrial organisms. Migration appears to be the dominant mechanism of change within PETM terrestrial ecosystems, not only within the mammal and plant records, but also among early Palaeogene turtle faunas. This shifting of geographic distributions introduced new and unique taxonomic assemblages to PETM terrestrial ecosystems, mainly through addition or substitution of taxa without

significant loss or modification of existing groups (the example of transient body-size reduction in North American mammals being an important exception). One of the striking aspects of terrestrial biotic change through the PETM is the lack of evidence for a PETM extinction event within any of the groups studied. This suggests a surprising level of adaptability within terrestrial ecosystems, although many details of the conditions and timing of PETM terrestrial environmental and biotic change remain to be resolved.

Hypotheses on causes and effects of the PETM

We have summarized the broad range of biotic, geochemical, and climatic changes associated with the massive release of ^{13}C -depleted carbon into the ocean-atmosphere system during the PETM. A major, ongoing research focus is to develop an integrated understanding of the cause and effect scenarios that brought about these changes, beginning with the carbon release itself. Several hypotheses describing the trigger and source of PETM carbon release have been proposed, and these must be critically evaluated in terms of our knowledge of the event's timing, of PETM carbon cycle changes, and of the biotic and climatic responses to carbon cycle perturbation. As described above, changes in the $\delta^{13}\text{C}$ values of the exogenic carbon pool and widespread dissolution of marine carbonates provide constraints on the magnitude of carbon released (Kennett and Stott 1991; Koch *et al.* 1992; Thomas *et al.* 2002; Zachos *et al.* 2005; Pagani *et al.* 2006). Orbital cycle- and helium-based age models give an order-of-magnitude constraint on the rates of release, which imply large, catastrophic or chronic fluxes of carbon occurred over $\sim 10^4$ years. Global warming of $5\text{--}6^\circ\text{C}$ implies large, sustained increases in atmospheric greenhouse gas levels (Dickens *et al.* 1995; Dickens 2001a). Critically, the existence of similar events in the early Eocene, including the ETM2 (Lourens *et al.* 2005) and ETM3 (Röhl *et al.* 2005), demonstrates that the PETM was not a unique event, and suggests ties between the initiation of these events and orbital cyclicity (Lourens *et al.* 2005).

Many proposed hypotheses cannot satisfy the latter constraint (Lourens *et al.* 2005). In theory, climatic extremes on a long-term gradual climate trend are expected to occur during eccentricity maxima, because at such times seasonal contrasts on both hemispheres are maximized, so that critical climate thresholds are likely to be surpassed. The climate of the late Palaeocene through early Eocene followed a long term warming trend,

as evidenced by benthic foraminifer $\delta^{18}\text{O}$ (Zachos *et al.* 2001) and many biotic proxies (e.g., Haq and Lohmann 1976; Hallock *et al.* 1991; Bujak and Brinkhuis 1998). This warming may have been caused by increasing atmospheric CO_2 levels through high volcanic activity in the North Atlantic Igneous Province (Eldholm and Thomas 1993; Schmitz *et al.* 2004; Thomas and Bralower 2005; MacLennan and Jones 2006) and/or along Indian Ocean spreading zones (Cogné and Humler 2006). The late Palaeocene is also characterized by a long-term decrease in benthic foraminiferal and bulk carbonate (and likely global exogenic) $\delta^{13}\text{C}$ after the major positive event in the mid Palaeocene (Corfield and Norris 1998; Zachos *et al.* 2001). The eccentricity maxima superimposed on these trends could have comprised thresholds for transient events and resulting climate change.

Spectral characteristics of magnetic susceptibility and colour reflectance records from Walvis Ridge show that the PETM, ETM2 (Lourens *et al.* 2005) and ETM3 (Röhl *et al.* 2005), all transient global greenhouse warming events, started on during short (100 kyr) and long-term (405 kyr) eccentricity maxima, suggesting an insolation-driven forcing mechanism (Lourens *et al.* 2005). Westerhold *et al.* (in press), however, using similar statistical treatments of high-resolution Fe and red/green (a^*) records of the same Walvis Ridge sites, argued that there were two short-term eccentricity cycles less between the PETM and ETM2 than indicated in (Lourens *et al.* 2005), with the implication that the PETM and ETM2 do not correspond exactly to a maximum in the long-term eccentricity cycle, but to one of the short-term (100kyr) eccentricity extremes superimposed on the long-term cycles. A definite clue to a possible orbital-based forcing mechanism is complicated, however, due to large uncertainties in available astronomical computations for the late Palaeocene to early Eocene (see Lourens *et al.* 2005). A more complete insight in possible forcing mechanisms may become available when a new generation of astronomical solutions is launched (Laskar, pers. comm.).

An important consequence of the hypothesis that the forcing of the PETM and similar (but less severe events) was orbitally-based is that triggering mechanisms involving unique tectonic, volcanic, or cosmic events can be excluded as the cause of the PETM. Proposed singular event include a comet impact (Kent *et al.* 2003; Cramer and Kent 2005), explosive volcanism (Bralower *et al.* 1997; Schmitz *et al.* 2004), intrusion-forced injection of thermogenic methane (Svensen *et al.* 2004), tectonic uplift-forced methane hydrate release

(MacLennan and Jones 2006), sub-lithospheric gas explosions (Phipps Morgan *et al.* 2004), and tectonically-forced desiccation of epicontinental seas (Higgins and Schrag 2006). Regardless of the specific orbital parameter association of the PETM, ETM2 and ETM3 and possible additional hyperthermal events, the simple fact that there were multiple events within the late Palaeocene and early Eocene implies a non-singular trigger as their cause.

What type of carbon-release scenarios could be triggered by orbital fluctuations in an greenhouse world and lead to rapid global warming and biotic change? In the present day situation, non-anthropogenic carbon reservoirs that can inject the required amount of ^{13}C -depleted carbon required to generate the CIE in the atmosphere and ocean on the required short time scale are scarce (Dickens *et al.* 1995; Dickens *et al.* 1997). One potential reservoir is formed by methane hydrates, although the size of the present hydrate reservoir is subject of discussion (Milkov 2004). The methane incorporated in the hydrates is produced by anoxic bacterial decomposition (average $\delta^{13}\text{C}$ of $\sim -60\text{‰}$) or thermogenic breakdown (average $\delta^{13}\text{C}$ of $\sim -30\text{‰}$) of organic matter (Kvenvolden 1988, 1993). In the present ocean, these hydrates are stable along continental slopes at relatively high pressure and low temperatures (at high latitudes at the surface, at lower latitudes below a few hundreds of m depth) and they have been argued to dissociate when pressure falls or temperature rises (MacDonald 1990; Xu *et al.* 2001). During the much warmer latest Palaeocene, hydrates were stable at deeper water depths (e.g., below $\sim 900\text{m}$) (Dickens *et al.* 1995), suggesting that the reservoir was smaller than at present (Buffett and Archer 2004). However, methane hydrates might have been present at greater depths than today (Dickens 2001b) if more organic matter was present further away from the continents than nowadays, perhaps in conjunction with lower oxygen content of the bottom waters resulting from higher temperatures, as suggested by benthic foraminiferal assemblages (Thomas and Zachos 2000; Thomas in press). In addition to concerns about the standing volume of methane hydrate at the time of the PETM, the rate of replenishment of these reservoirs is problematic if the CIEs related to ETM2 and ETM3 are also to be attributed to hydrate dissociation (Fehn *et al.* 2000). This might imply that a significant fraction of the hydrate reservoir was maintained through the PETM and ETM2, but would compound discrepancies between the implied and predicted hydrate inventories.

Dissociation of methane clathrates along continental slopes has been invoked to explain the CIE and part of the climatic warming (Dickens *et al.* 1995; Matsumoto 1995). In the present atmosphere CH₄ is oxidized to CO₂ within a decade. The atmospheric residence time of methane could increase at high atmospheric concentrations of this gas, but even this longer residence time has been argued to be only about 1-2 centuries (Schmidt and Schindell 2003). The relatively short residence time of CH₄ implies that the long-term (10⁴ years and more) climate effects of methane release would result from CO₂ forcing after the oxidation of methane in the atmosphere and/or oceans. As already pointed out by Dickens *et al.* (1997), the radiative forcing of the CO₂ resulting from the injection of ~2,000 Gt of biogenic methane is not enough to explain the magnitude of PETM climate warming (Dickens *et al.* 1997; Schmidt and Schindell 2003; Archer in press).

In their study to assess terrestrial and marine carbon burial rates, Kurtz *et al.* (2003) use the coupling between the carbon and sulphur cycles to quantify the very high rates of continental organic carbon burial through the middle Palaeocene qualitatively indicated by the global abundance of Palaeocene coals. These authors suggest that rapid oxidation (burning) of terrestrial organic carbon, in their words “*global conflagration*”, could have at least contributed to the CIE and climate warming. Terrestrial organic matter (~30‰) is much less ¹³C-depleted than biogenic methane hydrates, implying that much more carbon would have entered the atmosphere and ocean and provided a greater potential radiative forcing than that resulting from the release of methane hydrates (Kurtz *et al.* 2003; Higgins and Schrag 2006). The greatest challenge to the peat burning hypothesis is the lack of direct evidence for a massive loss of continental organic carbon at the PETM. High concentrations of macroscopic charcoal have been recorded locally at the PETM (Collinson *et al.* 2003), but these remains does not support a scenario of peat burning (Collinson *et al.* 2006). Huge deposits of upper Palaeocene peat deposits are still found today (e.g., Collinson *et al.* 2003), raising questions as to how these deposits survived the “*global conflagration*” and whether it is plausible that the late Palaeocene continental organic carbon reservoir contained sufficient, unseen organic-rich deposits to account for the PETM.

Problems thus still exist for the hypotheses of clathrate dissociation and continental organic carbon burning, although both are potentially climatically-induced and thus could be associated with orbital forcing. An orbitally-forced mechanism to trigger dissociation of methane hydrates might be found in temperatures of

intermediate waters, which increased due to warming of their high latitude source regions or due to orbitally-forced changes in circulation of deep waters. An orbitally-forced trigger for massive burning of peat could be found in the occurrence of droughts in regions with massive peat deposits. To invoke such mechanisms as a cause of the PETM with confidence, however, requires better documentation of the character, trends and dynamics of late Palaeocene climate, including its response to orbital cycles.

Thus, integration of available information on carbon cycle, climate change, biotic response as well as the time scale involved in the PETM still leaves us short of a clearly supported, all-encompassing cause and effect scenario for the PETM. Data on atmospheric CO₂ and CH₄ (although no proxy has been developed yet for the latter) concentrations through the event could help in evaluating the form and magnitude of injected carbon, which in combination with an improved understanding of the CIE magnitude would clearly distinguish between the hydrate and peat-burning hypotheses. As the causes and mechanisms of carbon release become clearer, focused analysis of the cascade of effects of this perturbation should eventually lead to the identification of mechanisms and feedbacks through which climate, environmental, and biotic change occurred (Bowen *et al.* 2004; Bowen *et al.* 2006; Sluijs 2006). More detailed studies of ETM2 and ETM3 are required to confirm that these events are similar in nature to the PETM and the degree to which these events are different from 'background climate' trends. Furthermore, comparative study of these events should help to resolve the importance of different climatic boundary conditions on the nature and magnitude of abrupt, transient, carbon-induced greenhouse events, improving our understanding of the dynamics of past hyperthermal events and their relevance to understanding climate change today.

Figure captions

1) Compilation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of planktonic foraminifera (surface dweller *Acarinina* and thermocline dweller *Subbotina* spp.; mostly single specimen),

benthic foraminifera (*Nuttallides truempyi*) and bulk carbonate from ODP Site 690 in the Weddell Sea (data from (Kennett and Stott 1991; Bains *et al.* 1999; Thomas *et al.* 2002; Kelly *et al.* 2005) and the soil carbonate nodule (Bowen *et al.* 2001) and dispersed organic carbon (DOC) (Magioncalda *et al.* 2004) $\delta^{13}\text{C}$ records from the Polecat Bench section in the Bighorn Basin, Wyoming, USA. BFE refers to the main phase of benthic foraminifer extinction according to (Thomas 2003). Mbsf = meters below sea floor.

2) Number of studies focused published per year on the PETM since the first publication on its CIE and warming in 1991. Numbers are based on a Web-of-Science search using the keywords Palaeocene, Palaeocene (both American and English spellings), Eocene, PETM, IETM and LPTM.

3) Shape and duration of the CIE (data from Bains *et al.* 1999) assuming the various options and uncertainties in sedimentation rates and background $^3\text{He}_{\text{ET}}$ fluxes calculated in Table 1. Options A, B and C represent scenarios I, V and VI from Table 1: A. $^3\text{He}_{\text{ET}}$ fluxes calculated from the measurements of C25 only (Table 1c) and sediment expansion not included, B. $^3\text{He}_{\text{ET}}$ fluxes calculated from the measurements of C24r and sediment expansion included, C. $^3\text{He}_{\text{ET}}$ fluxes calculated from the measurements of C25n through C24r and sediment expansion included. Dotted lines represent standard deviations of background flux measurements.

4) Palaeogeographic reconstruction of the earth during PETM times (modified from Scotese 2002) with the distribution of the acme of dinocyst *Apectodinium*. All studied PETM sections that bear dinocysts yield abundant *Apectodinium*. Records are from the North Sea (Bujak and Brinkhuis 1998 and references therein; Heilmann-Clausen 1985; Steurbaut *et al.* 2003; Sluijs 2006),

Greenland, Spitsbergen (e.g., Boulter and Manum 1989; Nohr-Hansen 2003), the Tethyan Ocean (N. Africa, Austria, Tunisia, Uzbekistan, Pakistan, India, Kazakhstan (e.g., Köthe *et al.* 1988; Bujak and Brinkhuis 1998; Iakovleva *et al.* 2001; Crouch *et al.* 2003a; Egger *et al.* 2003), equatorial Africa (JanDuChêne and Adediran 1984), the eastern (e.g., Edwards 1989; Sluijs 2006) and western U.S. (J. Lucas-Clark, pers. comm., 2003; Brinkhuis, Sluijs, unpublished), Barents Sea, South America (Brinkhuis, pers. obs.) and New Zealand (Crouch *et al.* 2001; Crouch *et al.* 2003b; Crouch and Brinkhuis 2005) and the Arctic Ocean (Sluijs *et al.* 2006).

5) Patterns of terrestrial biotic change through the PETM. A) Temporal sequence of changes in mammal and plant assemblages, shown relative to the palaeosol carbonate $\delta^{13}\text{C}$ curve for Polecat Bench, Wyoming, USA (carbon isotope values are shown here as anomalies relative to the average latest Palaeocene values; after (Bowen *et al.* 2006). B) Spatial pathways of migration thought to have been used by PETM intra- and inter-continental migrants. 1 - Directional exchange of mammals and turtles from Asia to North America and/or Europe. 2 - Northward range expansion of thermophilic plants from southern North America. 3 - Exchange of plant and mammal taxa between North America and Europe, including immigration of plant taxon to North America and homogenization of mammal faunas, including new PETM immigrants.

6) Magnetic susceptibility and a^* (red) colour reflectance records through the uppermost Palaeocene and lower Eocene at Site 1267, Walvis Ridge (from Zachos *et al.* 2004). The peaks are associated with the PETM and the early Eocene hyperthermal events ETM2 and ETM3. The age model used follows that of Zachos *et*

al. (2004), which has recently been updated (Lourens *et al.* 2005; Westerhold *et al.* in press).

Table caption

1) Calculation of sedimentation rates and $^3\text{He}_{\text{ET}}$ fluxes (in $\text{pcc.cm}^{-2}.\text{kyr}^{-1}$) through the upper Palaeocene – lower Eocene section of ODP Hole 690B. Average values and standard deviations for the background $^3\text{He}_{\text{ET}}$ content/g sediment (from Farley and Eltgroth, 2003) in Table 1c are used to calculate absolute background $^3\text{He}_{\text{ET}}$ fluxes through the following intervals: onset – termination C25n, onset C24r – ETM2 and onset C25n – ETM2. For these calculations we adopt the durations of these intervals from (Westerhold *et al.* in press) and exclude (Table 1a) and include (Table 1b) 11% core loss due to sediment expansion (see text).

References

- Ali, J.R., Kent, D.V. & Hailwood, E.A. 2000. Magnetostratigraphic reinvestigation of the Palaeocene/Eocene boundary interval in Hole 690B, Maud Rise, Antarctica. *Geophysical Journal International*, **141**: 639-646.
- Alroy, J., Koch, P.L. & Zachos, J.C. 2000. Global climate change and North American mammalian evolution. *Paleobiology*, **26**(4 SUPPS): 259-288.
- Archer, D. in press. Methane hydrates and anthropogenic climate change. *Geophysical Review Letters*.
- Aubry, M.-P., Berggren, W.A., Stott, L. & Sinha, A. 1996. The upper-Paleocene-lower Eocene stratigraphic record and the Paleocene-Eocene boundary carbon isotope excursion: implications for geochronology. In: R.W.O.B. Knox, R.M. Corfield and R.E. Dunay (Editors) *Correlation of the Early Paleogene in Northwest Europe. Geological Society of London Special Publication, Volume 101*. Geological Society of London London, pp. 353-380.

- Aubry, M.P. & Ouda, K. 2003. Introduction. *In: K. Ouda and M.P. Aubry (Editors) The Upper Paleocene-Lower Eocene of the Upper Nile Valley, Part 1, Stratigraphy*. Micropaleontology Press, New York, pp. ii-iv.
- Aubry, M.P., Lucas, S.G. & Berggren, W.A. (Editors), 1998. Late Paleocene - Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records. Columbia University Press, New York.
- Backman, J. 1986. Late Paleocene to middle Eocene calcareous nannofossil biochronology from Shatsky Rise, Walvis Ridge and Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **57**(43-59).
- Bains, S., Corfield, R.M. & Norris, G. 1999. Mechanisms of climate warming at the end of the Paleocene. *Science*, **285**: 724-727.
- Bains, S., Norris, R.D., Corfield, R.M. & Faul, K.L. 2000. Termination of global warmth at the Paleocene/Eocene boundary through productivity feedbacks. *Nature*, **407**: 171-174.
- Bains, S., Norris, R.D., Corfield, R.M., Bowen, G.J., Gingerich, P.D. & Koch, P.L. 2003. Marine-terrestrial linkages at the Paleocene-Eocene boundary. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene. Geological Society of America Special Paper 369*. Geological Society of America, Boulder, Colorado, USA, pp. 1-9.
- Beard, K.C. 1998. East of Eden; Asia as an important center of taxonomic origination in mammalian evolution. *In: K.C. Beard and M.R. Dawson (Editors) Dawn of the age of mammals in Asia; Bulletin of the Carnegie Museum of Natural History No. 34*, pp. 5-39.
- Beard, K.C. & Dawson, M.R. 1999. Intercontinental dispersal of Holarctic land mammals near the Paleocene/Eocene boundary; paleogeographic, paleoclimatic and biostratigraphic implications. *Bulletin de la Société Géologique de France*, **170**(5): 697-706.
- Beerling, D.J. 2000. Increased terrestrial carbon storage across the Palaeocene-Eocene boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**: 395-405.
- Berggren, W.A., Kent, D.V., Obradovich, J.D. & Swisher, C.C., III 1992. Towards a revised Paleogene geochronology. *In: D.R. Prothero and W.A. Berggren (Editors) Eocene-Oligocene Climatic and Biotic Evolution*. Princeton University Press, Princeton, pp. 29-45.
- Berggren, W.A., Kent, D.V., Swisher, C.C., III., & Aubry, M.-P. 1995. A revised Cenozoic geochronology and chronostratigraphy. *In: W.A. Berggren, D.V. Kent and J. Hardenbol (Editors) Geochronology, Time Scales and Global Stratigraphic Correlation*. SEPM (Society for Sedimentary Geology) Special Publication 54, Tulsa, Oklahoma, USA, pp. 129-212.
- Bice, K.L. & Marotzke, J. 2001. Numerical evidence against reversed thermohaline circulation in the warm Paleocene/Eocene ocean. *Journal of Geophysical Research*, **106**(C6): 11,529-11,542.
- Boersma, A., Premoli Silva, I. & Hallock, P. 1998. Trophic models for the well-mixed and poorly mixed warm oceans across the Paleocene/Eocene epoch boundary. *In: M.-P. Aubry, S.G. Lucas and W.A. Berggren (Editors) Late Paleocene - early Eocene climatic and biotic events in the marine and terrestrial records*. Columbia University Press, New York, pp. 204-213.
- Bolle, M.-P., Pardo, A., Hinrichs, K.-U., Adatte, T., von Salis, K., Burns, S., Keller, G. & Muzylev, N. 2000. The Paleocene-Eocene transition in the marginal northeastern Tethys (Kazakhstan and Uzbekistan). *International Journal of Earth Sciences*, **89**: 390-414.

- Boomer, I. & Whatley, R. 1995. Cenozoic Ostracoda from guyots in the western Pacific: Holes 865B and 866B (Leg 143). In: E.L. Winterer, W.W. Sager, J.V. Firth and J.M. Sinton (Editors) *Proceedings of the Ocean Drilling Program, Scientific Results 143*. Ocean Drilling Program, College Station, Texas, USA, pp. 75-86.
- Boulter, M.C. & Manum, S.B. 1989. The Brito-Arctic igneous province flora around the Paleocene/Eocene boundary. In: O. Eldholm, J. Thiede and E. Taylor (Editors) *Proceedings of the Ocean Drilling Program, Scientific Results*. Ocean Drilling Program, College Station, TX, pp. 663-680.
- Bowen, G.J., Beerling, D.J., Koch, P.L., Zachos, J.C. & Quattlebaum, T. 2004. A humid climate state during the Palaeocene/Eocene thermal maximum. *Nature*, **432**(7016): 495-499.
- Bowen, G.J., Koch, P.L., Meng, J., Ye, J. & Ting, S. 2005. Age and correlation of fossiliferous Late Paleocene-Early Eocene strata of the Erlian Basin, Inner Mongolia, China. *American Museum Novitates*, **3474**: 1-26.
- Bowen, G.J., Koch, P.K., Gingerich, P.D., Norris, R.D., Bains, S. & Corfield, R.M. 2001. Refined isotope stratigraphy across the continental Paleocene-Eocene boundary on Polecat Bench in the Northern Bighorn Basin. In: P.D. Gingerich (Editor) *Paleocene-Eocene Stratigraphy and Biotic Change in the Bighorn and Clarks Fork Basins, Wyoming*. University of Michigan Papers on Paleontology 33.
- Bowen, G.J., Clyde, W.C., Koch, P.L., Ting, S.Y., Alroy, J., Tsubamoto, T., Wang, Y.Q. & Wang, Y. 2002. Mammalian dispersal at the Paleocene/Eocene boundary. *Science*, **295**: 2062-2065.
- Bowen, G.J., Bralower, T.J., Delaney, M.L., Dickens, G.R., Kelly, D.C., Koch, P.L., Kump, L.R., Meng, J., Sloan, L.C., Thomas, E., Wing, S.L. & Zachos, J.C. 2006. Eocene Hyperthermal Event Offers Insight Into Greenhouse Warming. *EOS, Transactions, American Geophysical Union*, **87**(17): 165, 169.
- Bralower, T.J. 2002. Evidence of surface water oligotrophy during the Paleocene-Eocene thermal maximum: nannofossil assemblage data from Ocean Drilling Program Site 690, Maud Rise, Weddell Sea. *Paleoceanography*, **17**(2): 10.1029/2001PA000662.
- Bralower, T.J., Kelly, D.C. & Thomas, E. 2004. Comment on “Coccolith Sr/Ca records of productivity during the Paleocene-Eocene thermal maximum from the Weddell Sea” by Heather M. Stoll and Santo Bains. *Paleoceanography*, **17**(PA1014): doi:10.1029/2003PA000953.
- Bralower, T.J., Thomas, D.J., Zachos, J.C., Hirschmann, M.M., Röhl, U., Sigurdsson, H., Thomas, E. & Whitney, D.L. 1997. High-resolution records of the late Paleocene thermal maximum and circum-Caribbean volcanism: Is there a causal link? *Geology*, **25**(11): 963-966.
- Bralower, T.J., Zachos, J.C., Thomas, E., Parrow, M., Paull, C.K., Kelly, D.C., Premoli Silva, I., Sliter, W.V. & Lohmann, K.C. 1995. Late Paleocene to Eocene paleoceanography of the equatorial Pacific Ocean: stable isotopes recorded at Ocean Drilling Program Site 865, Allison Guyot. *Paleoceanography*, **10**: 841-865.
- Brinkhuis, H. 1994. Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (Northeast Italy): biostratigraphy and palaeoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**: 121-163.
- Brinkhuis, H., Romein, A.J.T., Smit, J. & Zachariasse, W.J. 1994. Danian-Selandian dinoflagellate cysts from lower latitudes with special reference to the El Kef section, NW Tunisia. *Geologiska Föreningens i Stockholm Förhandlingar (GFF; Transactions of the Geological Society in Stockholm)*, **116**(46-48).

- Brinkhuis, H., Schouten, S., Collinson, M.E., Sluijs, A., Damsté, J.S.S., Dickens, G.R., Huber, M., Cronin, T.M., Onodera, J., Takahashi, K., Bujak, J.P., Stein, R., van der Burgh, J., Eldrett, J.S., Harding, I.C., Lotter, A.F., Sangiorgi, F., Cittert, H.v.K.-v., de Leeuw, J.W., Matthiessen, J., Backman, J., Moran, K. & the Expedition, S. 2006. Episodic fresh surface waters in the Eocene Arctic Ocean. *Nature*, **441**(7093): 606-609.
- Buffett, B. & Archer, D. 2004. Global inventory of methane clathrate: sensitivity to changes in the deep ocean. *Earth and Planetary Science Letters*, **227**(3-4): 185-199.
- Bujak, J.P. & Brinkhuis, H. 1998. Global warming and dinocyst changes across the Paleocene/Eocene Epoch boundary. In: M.-P. Aubry, S.G. Lucas and W.A. Berggren (Editors) *Late Paleocene - early Eocene biotic and climatic events in the marine and terrestrial records*. Columbia University Press, New York, pp. 277-295.
- Butler, R.F., Gingerich, P.D. & Lindsay, E.H. 1981. Magnetic polarity stratigraphy and biostratigraphy of Paleocene and lower Eocene continental deposits, Clarks Fork Basin, Wyoming. *Journal of Geology*, **89**: 299-316.
- Caballero, R. & Langen, P.L. 2005. The dynamic range of poleward energy transport in an atmospheric general circulation model. *Geophysical Research Letters*, **32**(L02705): doi:10.1029/2004GL021581.
- Caldeira, K. & Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. *Nature*, **425**(6956): 365-365.
- Cande, S. & Kent, D.V. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **111**: 6093-6095.
- Charisi, S.D. & Schmitz, B. 1998. Paleocene to early Eocene paleoceanography of the Middle East: the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes from foraminiferal calcite. *Paleoceanography*, **13**(1): 106-118.
- Clyde, W.C. & Gingerich, P.D. 1998. Mammalian community response to the latest Paleocene thermal maximum: An isotaphonomic study in the northern Bighorn Basin, Wyoming. *Geology*, **26**: 1011-1014.
- Clyde, W.C., Khan, I.H. & Gingerich, P.D. 2003. Stratigraphic response and mammalian dispersal during initial India-Asia collision: Evidence from the Ghazij Formation, Balochistan, Pakistan. *Geology*, **31**(12): 1097-1100.
- Cogné, J.-P. & Humler, E. 2006. Trends and rhythms in global seafloor generation rate. *Geochemistry, Geophysics, Geosystems*, **7**(Q03011): doi:10.1029/2005GC001148.
- Cojan, I., Moreau, M.G. & Stott, L.E. 2000. Stable carbon isotope stratigraphy of the Paleogene pedogenic series of southern France as a basis for continental-marine correlation. *Geology*, **28**(3): 259-262.
- Collinson, M.E., Hooker, J.J. & Grocke, D.R. 2003. Cobham lignite bed and penecontemporaneous macrofloras of southern England: A record of vegetation and fire across the Paleocene-Eocene Thermal Maximum. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369. Geological Society of America, Boulder, Colorado, pp. 333-349.
- Collinson, M.E., Steart, D., Handley, L., Pancost, R., Scott, A.C., Glasspool, I., Hooker, J. & Stott, A. 2006. Fire regimes and palaeoenvironments across the onset of the Palaeocene/Eocene thermal maximum, S. England, Climate and Biota of the Early Paleogene, Bilbao.
- Colosimo, A.B., Bralower, T.J. & Zachos, J.C. 2005. Evidence for lysocline shoaling at the Paleocene/Eocene Thermal Maximum on Shatsky rise, northwest Pacific. In: T.J.

- Bralower, I. Premoli-Silva and M.J. Malone (Editors) *Proceedings of the Ocean Drilling Program 198*, Available from World Wide Web: <http://www-odp.tamu.edu/publications/198_SR/VOLUME/CHAPTERS/112.PDF>, pp. 1-36.
- Corfield, R.M. & Norris, R.D. 1998. The Oxygen and Carbon Isotopic Context of the Paleocene/Eocene Epoch Boundary. *In: M.-P. Aubry, S.G. Lucas and W.A. Berggren (Editors) Late Paleocene-early Eocene climatic and biotic events in the marine and terrestrial records*. Columbia University Press, New York, pp. 124-137.
- Cramer, B.S. & Kent, D.V. 2005. Bolide summer: The Paleocene/Eocene thermal maximum as a response to an extraterrestrial trigger. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **224**(1-3): 144-166.
- Cramer, B.S., Wright, J.D., Kent, D.V. & Aubry, M.-P. 2003. Orbital climate forcing of $\delta^{13}\text{C}$ excursions in the late Paleocene–early Eocene (chrons C24n–C25n). *Paleoceanography*, **18**(4): 10.1029/2003PA000909.
- Cramer, B.S., Aubry, M.-P., Miller, K.G., Olsson, R.K., Wright, J.D. & 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.
- Crouch, E.M. & Visscher, H. 2003. Terrestrial vegetation record across the initial Eocene thermal maximum at the Tawanui marine section, New Zealand. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, pp. 351-363.
- Crouch, E.M. & Brinkhuis, H. 2005. Environmental change across the Paleocene-Eocene transition from eastern New Zealand: A marine palynological approach. *Marine Micropaleontology*, **56**(3-4): 138-160.
- Crouch, E.M., Brinkhuis, H., Visscher, H., Adatte, T. & Bolle, M.-P. 2003a. Late Paleocene–early Eocene dinoflagellate cyst records from the Tethys: Further observations on the global distribution of *Apectodinium*. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369. Geological Society of America, Boulder, Colorado, pp. 113-131.
- Crouch, E.M., Heilmann-Clausen, C., Brinkhuis, H., Morgans, H.E.G., Rogers, K.M., Egger, H. & Schmitz, B. 2001. Global dinoflagellate event associated with the late Paleocene thermal maximum. *Geology*, **29**(4): 315-318.
- Crouch, E.M., Dickens, G.R., Brinkhuis, H., Aubry, M.-P., Hollis, C.J., Rogers, K.M. & Visscher, H. 2003b. The *Apectodinium* acme and terrestrial discharge during the Paleocene-Eocene thermal maximum: new palynological, geochemical and calcareous nannoplankton observations at Tawanui, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **194**: 387-403.
- Delille, B., Harlay, J., Zondervan, I., Jacquet, S., Chou, L., Wollast, R., Bellerby, R.G.J., Frankignoulle, M., Vieira-Borges, A., Riebesell, U. & Gattuso, J.-P. 2005. Response of primary production and calcification to changes of pCO₂ during experimental blooms of the coccolithophorid *Emiliania huxleyi*. *Global Biogeochemical Cycles*, **19**(GB2023): doi:10.1029/2004GB002318.
- Dickens, G.R. 2000. Methane oxidation during the late Paleocene Thermal Maximum. *Bulletin de la Société Géologique de France*, **171**: 37-49.

- Dickens, G.R. 2001a. Carbon addition and removal during the Late Palaeocene Thermal Maximum: Basic theory with a preliminary treatment of the isotope record at Ocean Drilling Program Site 1051, Blake Nose. *In: D. Kroon, R.D. Norris and A. Klaus (Editors) Western North Atlantic Paleogene and Cretaceous Paleoceanography, Geol. Soc. London Spec. Publ. 183.*
- Dickens, G.R. 2001b. The potential volume of oceanic methane hydrates with variable external conditions. *Organic Geochemistry*, **32**: 1179-1193.
- Dickens, G.R., Castillo, M.M. & Walker, J.C.G. 1997. A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate. *Geology*, **25**(3): 259-262.
- Dickens, G.R., O'Neil, J.R., Rea, D.K. & Owen, R.M. 1995. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography*, **10**: 965-971.
- Dickens, G.R., Fewless, T., Thomas, E. & Bralower, T.J. 2003. Excess barite accumulation during the Paleocene/Eocene thermal maximum: Massive input of dissolved barium from seafloor gas hydrate reservoirs. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene, Geological Society of America Special Publication, 369.* Geological Society of America, Boulder, Colorado, pp. 11-23.
- Dupuis, C., Aubry, M.-P., Steurbaut, E., Berggren, W.A., Ouda, K., Magioncalda, R., Cramer, B.S., Kent, D.V., Speijer, R.P. & Heilmann-Clausen, C. 2003. The Dababiya Quarry Section: Lithostratigraphy, clay mineralogy, geochemistry and paleontology. *Micropaleontology*, **49**(Suppl_1): 41-59.
- Edwards, L.E. 1989. Dinoflagellate Cysts from the Lower Tertiary Formations, Haynesville Cores, Richmond County, Virginia *Geology and Paleontology of the Haynesville Cores - Northeastern Virginia Coastal Plain. U.S. Geological Survey professional paper 1489-C.* United States Government Printing Office, Washington, pp. 23.
- Egger, H., Heilmann-Clausen, C. & Schmitz, B. 2000. The Paleocene-Eocene boundary interval of a Tethyan deep-sea section and its correlation with the North Sea basin. *Bulletin de la Société Géologique de France*, **171**: 207-216.
- Egger, H., Fenner, J., Heilmann-Clausen, C., Rögl, F., Sachsenhofer, R. & Schmitz, B. 2003. Paleoproductivity of the northwestern Tethyan margin (Anthering section, Austria) across the Paleocene-Eocene transition. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene, Geological Society of America Special Paper 369.* Geological Society of America, Boulder, Colorado, pp. 133-146.
- Eldholm, O. & Thomas, E. 1993. Environmental impact of volcanic margin formation. *Earth and Planetary Science Letters*, **117**(3-4): 319-329.
- Erez, J. & Luz, B. 1983. Experimental paleotemperature equation for planktonic foraminifera. *Geochimica et Cosmochimica Acta*, **47**(6): 1025-1031.
- Ernst, S.R., Guasti, E., Dupuis, C. & 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**(1): 89-111.
- Farley, K.A. 2001. Extraterrestrial helium in seafloor sediments: identification, characteristics, and accretion rate over geologic time. *In: B. Peucker-Ehrinbrink and B. Schmitz (Editors) Accretion of Extraterrestrial Matter Throughout Earth's History.* Kluwer, New York, pp. 179-204.

- Farley, K.A. & Eltgroth, S.F. 2003. An alternative age model for the Paleocene-Eocene thermal maximum using extraterrestrial ^3He . *Earth and Planetary Science Letters*, **208**: 135-148.
- Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. & Millero, F.J. 2004. Impact of Anthropogenic CO_2 on the CaCO_3 System in the Oceans. *Science*, **305**(5682): 362-366.
- Fehn, U., Snyder, G. & Egeberg, P.K. 2000. Dating of Pore Waters with ^{129}I : Relevance for the Origin of Marine Gas Hydrates. *Science*, **289**(5488): 2332-2335.
- Fensome, R.A., Gocht, H. & Williams, G.L., 1996. The Eisenack Catalog of Fossil Dinoflagellates. New Series, **4**. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, 2009-2548 pp.
- Florindo, F. & Roberts, A.P. 2005. Eocene-Oligocene magnetobiochronology of ODP Sites 689 and 690, Maud Rise, Weddell Sea, Antarctica. *Geological Society of America Bulletin*, **117**(1/2): 46-66.
- Fourtanier, E. 1991. Paleocene and eocene diatom stratigraphy and taxonomy of eastern Indian Ocean Site 752. In: J. Weissel, J. Peirce, E. Taylor, J. Alt and E. AL. (Editors) *Proceeding of the Ocean Drilling Program, Scientific Results 121*. Texas A&M University, College Station, Texas, USA, pp. 171-187.
- Fricke, H.C. & Wing, S.L. 2004. Oxygen isotope and paleobotanical estimates of temperature and $\delta^{18}\text{O}$ -latitude gradients over North America during the early Eocene. *American Journal of Science*, **304**(7): 612-635.
- Fricke, H.C., Clyde, W.C., O'Neil, J.R. & Gingerich, P.D. 1998. Evidence for rapid climate change in North America during the latest Paleocene thermal maximum: oxygen isotope compositions of biogenic phosphate from the Bighorn Basin (Wyoming) *Earth and Planetary Science Letters*, **160**(1-2): 193-208.
- Galeotti, S., Kaminski, M.A., Coccioni, R. & Speijer, R.P. 2005. High resolution deep water agglutinated foraminiferal records across the Paleocene/Eocene transition in the Contessa Road Section (Italy). In: M. Bubik and M.A. Kaminski (Editors) *Proceedings of the Sixth International Workshop on Agglutinated Foraminifera (Grzybowski Foundation Special Publication, Volume 8*.
- Gavrilov, Y., Shcherbinina, E.A. & Oberhänsli, H. 2003. Paleocene-Eocene boundary events in the northeastern Peri-Tethys. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369. Geological Society of America, Bolder, Colorado, pp. 147-168.
- Gervais, P. 1877. Enumeration de quelques ossements d'animaux vertebres recueillis aux environs de Reims par M. Lemoine. *Journal de Zoologie*, **6**: 74-79.
- Gibbs, S.J., Bralower, T.J., Bown, P.R., Zachos, J.C. & Bybell, L.M. 2006. Shelf and open-ocean calcareous phytoplankton assemblages across the Paleocene-Eocene Thermal Maximum: Implications for global productivity gradients. *Geology*, **34**(4): 233-236.
- Gibson, T.G. & Bybell, L.M. 1994. Sedimentary Patterns across the Paleocene-Eocene boundary in the Atlantic and Gulf coastal plains of the United States. *Bulletin de la Société Belge de Géologie*, **103**(3-4): 237-265.
- Gibson, T.G., Bybell, L.M. & Owens, J.P. 1993. Latest Paleocene lithologic and biotic events in neritic deposits of Southwestern New Jersey. *Paleoceanography*, **8**(4): 495-514.
- Gibson, T.G., Bybell, L.M. & Mason, D.B. 2000. Stratigraphic and climatic implications of clay mineral changes around the Paleocene/Eocene boundary of the northeastern US margin. *Sedimentary Geology*, **134**: 65-92.

- Gingerich, P.D. 1989. New earliest Wasatchian mammalian fauna from the Eocene of Northwestern Wyoming: Composition and diversity in a rarely sampled high-floodplain assemblage. *University of Michigan Papers on Paleontology*, **28**: 1-97.
- Gingerich, P.D. 2000. Paleocene-Eocene boundary and continental vertebrate faunas of Europe and North America. In: B. Schmitz, B. Sundquist and F.P. Andreasson (Editors) *Early Paleogene Warm Climates and Biosphere Dynamics*. GFF (Geologiska Föreningens Förhandlingar), Geological Society of Sweden. , Uppsala, pp. 57-59.
- Gingerich, P.D. 2006. Environment and evolution through the Paleocene-Eocene thermal maximum. *Trends in Ecology & Evolution*, **21**(5): 246-253.
- Gingerich, P.D. & Clyde, W.C. 2001. Overview of mammalian biostratigraphy of the Paleocene-Eocene Fort Union and Willwood formations of the Bighorn and Clarks Fork basins. In: P.D. Gingerich (Editor) *Paleocene-Eocene Stratigraphy and Biotic Change in the Bighorn and Clarks Fork Basins, Wyoming*. University of Michigan Papers on Paleontology, **33**, pp. 1-14.
- Giusberti, L., Rio, D., Agnini, C., Backman, J., Fornaciari, E., Tateo, F. & Oddone, M. in press. An expanded marine PETM section in the Venetian Pre-Alps, Italy. *Geological Society of America Bulletin*.
- Gradstein, F.M., Ogg, J.G. & Smith, A.G., 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge.
- Gradstein, F.M., Kaminski, M.A., Berggren, W.A., Kristiansen, I.L. & D'Ioro, M.A. 1994. Cenozoic biostratigraphy of the North Sea and Labrador Shelf. *Micropaleontology*, **40 Supplement**: 152.
- Guasti, E., Kouwenhoven, T.J., Brinkhuis, H. & Speijer, R.P. 2005. Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, Tunisia). *Marine Micropaleontology*, **55**(1-2): 1-17.
- Hallock, P., Premoli Silva, I. & Boersma, A. 1991. Similarities between planktonic and larger foraminiferal evolutionary trends through Paleogene paleoceanographic changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **83**(1-3): 49-64.
- Haq, B.U. & Lohmann, G.P. 1976. Early Cenozoic calcareous nannoplankton biogeography of the Atlantic Ocean. *Marine Micropaleontology*, **1**: 119-194.
- Harrington, G.J. 2003. Geographic patterns in the floral response to Paleocene-Eocene warming. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, pp. 381-393.
- Harrington, G.J. & Kemp, S.J. 2001. US Gulf Coast vegetation dynamics during the latest Palaeocene. *Palaeogeography Palaeoclimatology Palaeoecology*, **167**(1-2): 1-21.
- Harrington, G.J., Kemp, S.J. & Koch, P.L. 2004. Palaeocene-Eocene paratropical floral change in North America: Responses to climate change and plant immigration. *Journal of the Geological Society*, **161**: 173-184.
- Heilmann-Clausen, C. 1985. Dinoflagellate stratigraphy of the Uppermost Danian to Ypresian in the Viborg 1 borehole, Central Jylland, Denmark. *DGU A7*: 1-69.
- Heilmann-Clausen, C. & Egger, H. 2000. The Anthering outcrop (Austria), a key-section for correlation between Tethys and Northwestern Europe near the Paleocene/Eocene boundary. In: B. Schmitz, B. Sundquist and F.P. Andreasson (Editors) *Early Paleogene Warm Climates and Biosphere Dynamics*. GFF (Geologiska Föreningens Förhandlingar), Geological Society of Sweden. Uppsala, pp. 69.

- Higgins, J.A. & Schrag, D.P. 2006. Beyond methane: Towards a theory for the Paleocene-Eocene Thermal Maximum. *Earth and Planetary Science Letters*, **245**(3-4): 523-537.
- Hollis, C.J. in press. Radiolarian faunal turnover through the Paleocene-Eocene transition, Mead Stream, New Zealand. *Eclogae Geologicae Helvetiae*.
- Hollis, C.J., Dickens, G.R., Field, B.D., Jones, C.M. & Percy Strong, C. 2005a. The Paleocene-Eocene transition at Mead Stream, New Zealand: a southern Pacific record of early Cenozoic global change. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **215**(3-4): 313-343.
- Hollis, C.J., Field, B.D., Jones, C.M., Strong, C.P., Wilson, G.J. & Dickens, G.R. 2005b. Biostratigraphy and carbon isotope stratigraphy of uppermost Cretaceous-lower Cenozoic Muzzle Group in middle Clarence valley, New Zealand. *Journal of the Royal Society of New Zealand*, **35**(3): 345-383.
- Holroyd, P.A., Hutchison, J.H. & Strait, S.G. 2001. Turtle diversity and abundance through the lower Eocene Willwood Formation of the southern Bighorn Basin. *University of Michigan Papers on Paleontology*, **33**: 97-107.
- Hooker, J.J. 1998. Mammalian faunal change across the Paleocene-Eocene transition in Europe. In: M.P. Aubry, S. Lucas and W.A. Berggren (Editors) *Late Paleocene-Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records*. Columbia University Press, New York, pp. 428-450.
- Huber, M., Sloan, L.C. & Shellito, C.J. 2003. Early Paleogene oceans and climate: A fully coupled modeling approach using the NCAR CCSM. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Palaeogene*, Geological Society of America Special Paper 369. Geological Society of America, Boulder, Colorado, pp. 25-47.
- Iakovleva, A.I., Brinkhuis, H. & Cavagnetto, C. 2001. Late Palaeocene-Early Eocene dinoflagellate cysts from the Turgay Strait, Kazakhstan; correlations across ancient seaways. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **172**: 243-268.
- Intergovernmental Panel on Climate Change 2001. Climate Change 2001, The Scientific Basis. http://www.grida.no/climate/ipcc_tar/wg1/index.htm.
- Jackson, S.T. & Overpeck, J.T. 2000. Responses of plant populations and communities to environmental changes of the late Quaternary. *Paleobiology*, **26**(4 SUPPS): 194-220.
- JanDuChêne, R.E. & Adediran, S.A. 1984. Late Paleocene to Early Eocene Dinoflagellates from Nigeria. *Cahiers de Micropaléontologie*, **3-1984**: 88.
- Jaramillo, C.A. & Dilcher, D.L. 2000. Microfloral diversity patterns of the late Paleocene-Eocene interval in Colombia, northern South America. *Geology*, **28**(9): 815-818.
- Kaminski, M.A., Kuhnt, W.A. & Radley, J.D. 1996. Palaeocene-Eocene deep water agglutinated foraminifera from the Namibian Flysch (Rif, Northern Morocco): their significance for the palaeoceanography of the Gibraltar Gateway. *Journal of Micropalaeontology*, **15**: 1-19.
- Kelly, D.C., Bralower, T.J. & Zachos, J.C. 1998. Evolutionary consequences of the latest Paleocene thermal maximum for tropical planktonic foraminifera. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **141**: 139-161.
- Kelly, D.C., Zachos, J.C., Bralower, T.J. & Schellenberg, S.A. 2005. Enhanced terrestrial weathering/runoff and surface ocean carbonate production during the recovery stages of the Paleocene-Eocene thermal maximum. *Paleoceanography*, **20**(PA4023): doi:10.1029/2005PA001163.

- Kelly, D.C., Bralower, T.J., Zachos, J.C., Premoli Silva, I. & Thomas, E. 1996. Rapid diversification of planktonic foraminifera in the tropical Pacific (ODP Site 865) during the late Paleocene thermal maximum. *Geology*, **24**(423-426).
- Kennett, J.P. & Stott, L.D. 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. *Nature*, **353**: 225-229.
- Kent, D.V., Cramer, B.S., Lanci, L., Wang, D., Wright, J.D. & Voo, R.V.d. 2003. A case for a comet impact trigger for the Paleocene/Eocene thermal maximum and carbon isotope excursion. *Earth and Planetary Science Letters*, **211**: 13-26.
- Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L. & Robbins, L.L., 2006. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research. available at: <http://www.isse.ucar.edu/florida/>. Institute for the Study of Society and Environment, National Center for Atmospheric Research, 89 pp.
- Knox, R.W.O.B., Corfield, R.M. & Dunay, R.S. (Editors), 1996. Correlation of the Early Paleogene in Northwest Europe. Geological Society of London Special Publication, 101, London, UK.
- Koch, P.L., Zachos, J.C. & Gingerich, P.D. 1992. Correlation between isotope records in marine and continental carbon reservoirs near the Palaeocene/Eocene boundary. *Nature*, **358**: 319-322.
- Koch, P.L., Zachos, J.C. & Dettman, D.L. 1995. Stable isotope stratigraphy and paleoclimatology of the Paleogene Bighorn Basin (Wyoming, USA). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **115**: 61-89.
- Koch, P.L., Clyde, W.C., Hepple, R.P., Fogel, M.L., Wing, S.L. & Zachos, J.C. 2003. Carbon and oxygen isotope records from paleosols spanning the Paleocene-Eocene boundary, Bighorn Basin, Wyoming. In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper, Boulder, Colorado, pp. 49-64.
- Köthe, A., Khan, A.M. & Ashraf, M., 1988. Biostratigraphy of the Surghar Range, Salt Range, Sulaiman Range and the Kohat area, Pakistan, according to Jurassic through Paleogene Calcareous Nannofossils and Paleogene Dinoflagellates. *Geologisches Jahrbuch, Reihe B*, **71**. Bundesanstalt für Geowissenschaften und Rohstoffe und den Geologischen Landesämtern in der Bundesrepublik Deutschland, Hannover, 87 pp.
- Krause, D.W. & Maas, M.C. 1990. The biogeographic origins of late Paleocene-early Eocene mammalian immigrants to the western interior of North America. In: T.M. Bown and K.D. Rose (Editors) *Dawn of the age of mammals in the northern part of the Rocky Mountain interior, North America*. Geological Society of America, Boulder, pp. 71-105.
- Kurtz, A., Kump, L.R., Arthur, M.A., Zachos, J.C. & Paytan, A. 2003. Early Cenozoic decoupling of the global carbon and sulfur cycles. *Paleoceanography*, **18**(1090, doi:10.1029/2003PA000908).
- Kvenvolden, K.A. 1988. Methane hydrate - a major reservoir of carbon in the shallow geosphere? *Chemical Geology*, **71**: 41-51.
- Kvenvolden, K.A. 1993. Gas hydrates: Geological perspective and global change. *Review of Geophysics*, **31**: 173-187.
- Lourens, L.J., Sluijs, A., Kroon, D., Zachos, J.C., Thomas, E., Röhl, U., Bowles, J. & Raffi, I. 2005. Astronomical pacing of late Palaeocene to early Eocene global warming events. *Nature*, **435**(7045): 1083-1087.
- Lu, G. & Keller, G. 1993. The Paleocene-Eocene transition in the Antarctic Indian Ocean: Inference from planktic foraminifera. *Marine Micropaleontology*, **21**(1-3): 101-142.

- Lu, G. & Keller, G. 1995. Ecological stasis and saltation: species richness change in planktic foraminifera during the late Paleocene to early Eocene, DSDP Site 577. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **117**(3-4): 211-227.
- MacDonald, G.J. 1990. Role of methane clathrates in past and future climates. *Climatic Change*, **16**(3): 247-281.
- MacLennan, J. & Jones, S.M. 2006. Regional uplift, gas hydrate dissociation and the origins of the Paleocene-Eocene Thermal Maximum. *Earth and Planetary Science Letters*, **245**(1-2): 65-80.
- Magioncalda, R., Dupuis, C., Smith, T., Steurbaut, E. & Gingerich, P.D. 2004. Paleocene-Eocene carbon isotope excursion in organic carbon and pedogenic carbonate: Direct comparison in a continental stratigraphic section. *Geology*, **32**(7): 553-556.
- Marland, G., Boden, T.A. & Andres, R.J. 2005. Global, Regional, and National CO₂ Emissions *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.
- Martini, E. 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: A. Farinacci (Editor) *Proceedings of the II Planktonic Conference, Roma 1970. Vol. 2*. Edizioni Tecnoscienza, Rome, pp. 739-785.
- Matsumoto, R. 1995. Causes of the $\delta^{13}\text{C}$ anomalies of carbonates and a new paradigm "gas-hydrate hypothesis". *Journal of the Geological Society of Japan*, **101**: 902-904.
- McKenna, M.C. 1983. Holarctic landmass rearrangement, cosmic events, and Cenozoic terrestrial organisms. *Annals of the Missouri Botanical Garden*, **70**: 459-489.
- Meng, J., Bowen, G.J., Ye, J., Koch, P.L., Ting, S., Li, Q. & Jin, X. 2004. Gomphos elkema (Glires, Mammalia) from the Erlian Basin: Evidence for the Early Tertiary Bumbanian Land Mammal Age in Nei-Mongol, China. *American Museum Novitates*, **3425**: 1-25.
- Milkov, A.V. 2004. Global estimates of hydrate-bound gas in marine sediments: how much is really out there? *Earth-Science Reviews*, **66**(3-4): 183-197.
- Miller, K.G., Wright, J.D. & Browning, J.V. 2005. Visions of ice sheets in a greenhouse world. *Marine Geology*, **217**(3-4): 215-231.
- Monechi, S., Angori, E. & von-Salis, K. 2000. Calcareous nannofossil turnover around the Paleocene/Eocene transition at Alamedilla (southern Spain). *Bulletin de la Société Géologique de France*, **171**: 477-489.
- Mukhopadhyay, S., Farley, K.A. & Montanari, A. 2001. A 35 Myr record of helium in pelagic limestones from Italy: implications for interplanetary dust accretion from the early Maastrichtian to the middle Eocene. *Geochimica et Cosmochimica Acta*, **65**(4): 653-669.
- Nohr-Hansen, H. 2003. Dinoflagellate cyst stratigraphy of the Palaeogene strata from the Hellefisk-1, Ikermiut-1, Kangamiut-1, Nukik-1, Nukik-2 and Qulleq-1 wells, offshore West Greenland. *Marine and Petroleum Geology*, **20**(9): 987-1016.
- Norris, R.D. & Röhl, U. 1999. Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition. *Nature*, **401**: 775-778.
- Nunes, F. & Norris, R.D. 2006. Abrupt reversal in ocean overturning during the Palaeocene/Eocene warm period. *Nature*, **439**(7072): 60-63.
- Okada, H. & Bukry, D. 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). *Marine Micropaleontology*, **5**: 321-325.
- Oreshkina, T.V. & Oberhänsli, H. 2003. Diatom turnover in the early Paleogene diatomite of the Sengiley section, middle Povolzhie, Russia: A response to the initial Eocene thermal

- maximum? In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and consequences of globally warm climates in the early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, USA, pp. 169-179.
- Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y. & Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**(7059): 681-686.
- Ortiz, N. 1995. Differential patterns of benthic foraminiferal extinctions near the Paleocene/Eocene boundary in the North Atlantic and western Tethys. *Marine Micropaleontology*, **26**: 341-359.
- Overpeck, J.T., Webb, R.S. & Webb III, T. 1992. Mapping eastern North American vegetation change of the past 18 ka: No-analogs and the future. *Geology*, **20**: 1071-1074.
- Pagani, M., Pedentchouk, N., Huber, M., Sluijs, A., Schouten, S., Brinkhuis, H., Sinninghe Damsté, J.S., Dickens, G.R. & Expedition-Scientists 2006. Arctic hydrology during global warming at the Palaeocene-Eocene thermal maximum. *Nature*, **442**(7103): 671-675.
- Pak, D.K. & Miller, K.G. 1992. Paleocene to Eocene benthic foraminiferal isotopes and assemblages: Implications for deep water circulation. *Paleoceanography*, **7**(4): 405-422.
- Pardo, A., Keller, G., Molina, E. & Canudo, J. 1997. Planktic foraminiferal turnover across the Paleocene-Eocene transition at DSDP Site 401, Bay of Biscay, North Atlantic. *Marine Micropaleontology*, **29**(2): 129-158.
- Pearson, P.N. & Berggren, W.A. 2005. Revised Tropical to Subtropical Paleogene Planktonic Foraminiferal Zonation. *Journal of Foraminiferal Research* **35**(4): 279-298.
- Peters, R.B. & Sloan, L.C. 2000. High concentrations of greenhouse gases and polar stratospheric clouds: A possible solution to high-latitude faunal migration at the latest Paleocene thermal maximum. *Geology*, **28**(11): 979-982.
- Phipps Morgan, J., Reston, T.J. & Ranero, C.R. 2004. Contemporaneous mass extinctions, continental flood basalts, and 'impact signals' are mantle plume-induced lithospheric gas explosions the causal link? *Earth and Planetary Science Letters*, **217**(3-4): 263-284.
- Pierrehumbert, R.T. 2002. The hydrologic cycle in deep-time climate problems. *Nature*, **419**(6903): 191-198.
- Popp, B.N., Laws, E.A., Bidigare, R.R., Dore, J.E., Hanson, K.L. & Wakeham, S.G. 1998. Effect of Phytoplankton Cell Geometry on Carbon Isotopic Fractionation. *Geochimica et Cosmochimica Acta*, **62**(1): 69-77.
- Powell, A.J., Brinkhuis, H. & Bujak, J.P. 1996. Upper Paleocene - Lower Eocene dinoflagellate cyst sequence biostratigraphy of southeast England. In: R.W.O.B. Knox, R.M. Corfield and R.S. Dunay (Editors) *Correlation of the Early Paleogene in Northwest Europe*, Geological Society Special Publication, **101**, pp. 145-183.
- Pross, J. & Brinkhuis, H. 2005. Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene; a synopsis of concepts. *Paläontologische Zeitschrift*, **79**(1): 53-59.
- Pujalte, V., Orue-Etxebarria, X., Schmitz, B., Tosquella, J., Baceta, J.I., Payros, A., Bernaola, G., Caballero, F. & Apellaniz, E. 2003. Basal Ilerdian (earliest Eocene) turnover of larger Foraminifera: Age constraints based on calcareous plankton and $\delta^{13}\text{C}$ isotopic profiles from new southern Pyrenean sections (Spain). In: S.L. Wing, P.D. Gingerich, B.

- Schmitz and E. Thomas (Editors) *Causes and consequences of globally warm climates in the early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, USA, pp. 205–221.
- Radionova, E.P., Khokhlova, I.E., Baniamovskii, V.N., Shcherbinina, E.A., Iakovleva, A.I. & Sadchikova, T.A. 2001. The Paleocene/Eocene transition in the northeastern Peri-Tethys area: Sokolovskii key section of the Turgay Passage (Kazakhstan). *Bulletin de la Société Géologique de France*, **172**(2): 245-256.
- Raffi, I., Backman, J. & Pälike, H. 2005. Changes in calcareous nannofossil assemblages across the Paleocene/Eocene transition from the paleo-equatorial Pacific Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **226**(1-2): 93-126.
- Ravizza, G., Norris, R.N. & Blusztajn, J. 2001. An osmium isotope excursion associated with the late Paleocene thermal maximum: Evidence of intensified chemical weathering. *Paleoceanography*, **16**: 155-163.
- Robert, C. & Kennett, J.P. 1994. Antarctic subtropical humid episode at the Paleocene-Eocene boundary: clay mineral evidence. *Geology*, **22**(211-214).
- Röhl, U., Norris, R.D. & Ogg, J.G. 2003. Cyclostratigraphy of upper Paleocene and lower Eocene sediments at Blake Nose Site 1051 (western North Atlantic). In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369. Geological Society of America., Boulder, Colorado, pp. 567–589.
- Röhl, U., Bralower, T.J., Norris, G. & Wefer, G. 2000. A new chronology for the late Paleocene thermal maximum and its environmental implications. *Geology*, **28**: 927-930.
- Röhl, U., Westerhold, T., Monechi, S., Thomas, E., Zachos, J.C. & Donner, B. 2005. The third and final early Eocene thermal maximum: characteristics, timing, and mechanisms of the "X" event., Geological Society of America Annual Meeting. Abstr. 37 (7), p. 264.
- Sanfilippo, A. & Nigrini, C. 1998. Upper Palaeocene-Lower Eocene deep-sea radiolarian stratigraphy and the Palaeocene-Eocene series boundary. In: M.-P. Aubry, S.G. Lucas and W.A. Berggren (Editors) *Late Palaeocene-Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records*. Columbia University Press, New York, pp. 244-276.
- Sanfilippo, A. & Blome, C.D. 2001. Biostratigraphic implications of mid-latitude Palaeocene-Eocene radiolarian faunas from Hole 1051A, ODP Leg 171B, Blake Nose, western North Atlantic. In: D. Kroon, R.D. Norris and A. Klaus (Editors) *Western North Atlantic Palaeogene and Cretaceous Palaeoceanography*. Geological Society, London, Special Publications 183, London, pp. 185-224.
- Scheibner, C., Speijer, R.P. & Marzouk, A.M. 2005. Turnover of larger foraminifera during the Paleocene-Eocene Thermal Maximum and paleoclimatic control on the evolution of platform ecosystems. *Geology*, **33**(6): 493-496.
- Schenau, S.J., Prins, M., de Lange, G.J. & Monnin, C. 2001. Barium accumulation in the Arabian Sea: Controls on barite preservation in marine sediments. *Geochimica et Cosmochimica Acta*, **65**(10): 1545-1556.
- Schmidt, G.A. & Schindell, D.T. 2003. Atmospheric composition, radiative forcing, and climate change as a consequence of a massive methane release from gas hydrates. *Paleoceanography*, **18**(1004): doi:10.1029/2002PA000757.
- Schmitz, B., Speijer, R.P. & Aubry, M.-P. 1996. Latest Paleocene benthic extinction event on the southern Tethyan shelf (Egypt): Foraminiferal stable isotopic ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) records. *Geology*, **24**(4): 347-350.

- Schmitz, B., Peucker-Ehrenbrink, B., Heilmann-Clausen, C., Åberg, G., Asaro, F. & Lee, C.-T.A. 2004. Basaltic explosive volcanism, but no comet impact, at the Paleocene-Eocene boundary: high-resolution chemical and isotopic records from Egypt, Spain and Denmark. *Earth and Planetary Science Letters*, **225**: 1-17.
- Scotese, C.R. 2002. <http://www.scotese.com>, (PALEOMAP website).
- Sexton, P.F., Wilson, P.A. & Norris, R.D. 2006. Testing the Cenozoic multisite composite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ curves: New monospecific Eocene records from a single locality, Demerara Rise (Ocean Drilling Program Leg 207). *Paleoceanography*, **21**(PA2019): doi: 10.1029/2005PA001253.
- Shackleton, N.J. 1967. Oxygen isotope analyses and Pleistocene temperatures reassessed. *Nature*, **215**: 15-17.
- Sluijs, A., 2006. Global Change during the Paleocene-Eocene thermal maximum. Laboratory of Palaeobotany and Palynology Foundation No. 21, Utrecht, The Netherlands, 228 pp.
- Sluijs, A., Pross, J. & Brinkhuis, H. 2005. From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. *Earth-Science Reviews*, **68**(3-4): 281-315.
- Sluijs, A., Schouten, S., Pagani, M., Woltering, M., Brinkhuis, H., Sinninghe Damsté, J.S., Dickens, G.R., Huber, M., Reichert, G.-J., Stein, R., Matthiessen, J., Lourens, L.J., Pedentchouk, N., Backman, J., Moran, K. & the Expedition, S. 2006. Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum. *Nature*, **441**(7093): 610-613.
- Smith, T. & Smith, R. 1995. Synthèse des données actuelles sur les vertébrés de la transition Paleocene-Eocene de Dormaal (Belgique). *Bulletin de la Société belge de Géologie*, **104**(1-2): 119-131.
- Smith, T., Rose, K., D. & Gingerich, P., D. 2006. Rapid Asia–Europe–North America geographic dispersal of earliest Eocene primate *Teilhardina* during the Paleocene–Eocene Thermal Maximum *Proceedings of the National Academy of Sciences of the United States of America*, **103**(30): 11223-11227.
- Speijer, R.P. & Schmitz, B. 1998. A benthic foraminiferal record of Paleocene sea level and trophic/redox conditions at Gebel Aweina, Egypt. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **137**(1-2): 79-101.
- Speijer, R.P. & 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.
- Speijer, R.P. & Morsi, A.-M.M. 2002. Ostracode turnover and sea-level changes associated with the Paleocene-Eocene thermal maximum. *Geology*, **30**(1): 23-26.
- Speijer, R.P., Schmitz, B. & van der Zwaan, G.J. 1997. Benthic foraminiferal extinction and repopulation in response to latest Paleocene Tethyan anoxia. *Geology*, **27**(8): 683–686.
- Spero, H.J., Bijma, J., Lea, D.W. & Bemis, B.E. 1997. Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes. *Nature*, **390**(6659): 497-500.
- Spiess, V. 1990. Cenozoic magnetostratigraphy of Leg 113 drill sites, Maud Rise, Weddell Sea, Antarctica. In: P.F. Barker, J.P. Kennett and e. al (Editors) *Proceedings of the Ocean Drilling Project, Initial Reports 113*, pp. 261-315.
- Steineck, P.L. & Thomas, E. 1996. The latest Paleocene crisis in the deep sea: Ostracode succession at Maud Rise, Southern Ocean. *Geology*, **24**(7): 583-586.

- Steurbaut, E., Magioncalda, R., Dupuis, C., Van Simaey, S., Roche, E. & Roche, M. 2003. Palynology, paleoenvironments, and organic carbon isotope evolution in lagoonal Paleocene-Eocene boundary settings in North Belgium. *In: S.L. Wing, P. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and consequences of Globally Warm Climates in the Early Paleogene, Geological Society of America Special Paper 369*. Geological Society of America, Boulder, Colorado, pp. 291-317.
- Stoll, H.M. 2005. Limited range of interspecific vital effects in coccolith stable isotopic records during the Paleocene-Eocene thermal maximum. *Paleoceanography*, **20**(PA1007): doi:10.1029/2004PA001046.
- Stoll, H.M. & Bains, S. 2003. Coccolith Sr/Ca records of productivity during the Paleocene-Eocene thermal maximum from the Weddell Sea. *Paleoceanography*, **18**(2): doi:10.1029/2002PA000875.
- Stott, L.D., Sinha, A., Thiry, M., Aubry, M.-P. & Berggren, W.A. 1996. Global $\delta^{13}\text{C}$ changes across the Paleocene-Eocene boundary; criteria for terrestrial-marine correlations. *In: R.W.O.B. Knox, R.M. Corfield and R.E. Dunay (Editors) Correlation of the Early Paleogene in Northwestern Europe, Geological Society London Special Publication, 101*. Geological Society of London, London, United Kingdom.
- Svensen, H., Planke, S., Malthes-Sørensen, A., Jamtveit, B., Myklebust, R., Eidem, T.R. & Rey, S.S. 2004. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. *Nature*, **429**: 542-545.
- Thomas, D.J. 2004. Evidence for deep-water production in the North Pacific Ocean during the early Cenozoic warm interval. *Nature*, **430**(6995): 65-68.
- Thomas, D.J. & Bralower, T.J. 2005. Sedimentary trace element constraints on the role of North Atlantic Igneous Province volcanism in late Paleocene-early Eocene environmental change. *Marine Geology*, **217**(3-4): 233-254.
- Thomas, D.J., Zachos, J.C., Bralower, T.J., Thomas, E. & Bohaty, S. 2002. Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum. *Geology*, **30**(12): 1067-1070.
- Thomas, E. 1989. Development of Cenozoic deep-sea benthic foraminiferal faunas in Antarctic waters. *Geological Society London Special Publication*, **47**: 283-296.
- Thomas, E. 1998. Biogeography of the late Paleocene benthic foraminiferal extinction. *In: M.-P. Aubry, S.G. Lucas and W.A. Berggren (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. 2003. Extinction and food at the seafloor: A high-resolution benthic foraminiferal record across the Initial Eocene Thermal Maximum, Southern Ocean Site 690. *In: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) Causes and Consequences of Globally Warm Climates in the Early Paleogene. Geological Society of America Special Paper 369*. Geological Society of America, Boulder, Colorado, pp. 319-332.
- Thomas, E. in press. Cenozoic mass extinctions in the deep sea: what perturbs the largest habitat on earth? *Geological Society of America Special Paper*.
- Thomas, E. & Shackleton, N.J. 1996. The Palaeocene-Eocene benthic foraminiferal extinction and stable isotope anomalies. *In: R.W.O.B. Knox, R.M. Corfield and R.E. Dunay (Editors) Correlation of the Early Paleogene in Northwestern Europe, Geological Society London Special Publication, 101*. Geological Society of London, London, United Kingdom, pp. 401-441.

- Thomas, E. & Zachos, J.C. 2000. Was the late Paleocene thermal maximum a unique event? *Geologiska Föreningens i Stockholm Förhandlingar (GFF; Transactions of the Geological Society in Stockholm)*, **122**: 169-170.
- Thomas, E., Zachos, J.C. & Bralower, T.J. 2000. Deep-sea environments on a warm Earth: Latest Paleocene-early Eocene. *In*: B.T. Huber, K. MacLeod and S.L. Wing (Editors) *Warm Climates in Earth History*. Cambridge University Press, pp. 132-160.
- Ting, S., Bowen, G.J., Koch, P.L., Clyde, W.C., Wang, Y., Wang, Y. & McKenna, M.C. 2003. Biostratigraphic, chemostratigraphic, and magnetostratigraphic study across the Paleocene/Eocene boundary in the Hengyang Basin, Hunan, China. *In*: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, pp. 521-535.
- Tjalsma, R.C. & Lohmann, G.P., 1983. Paleocene-Eocene bathyal and abyssal benthic foraminifera from the Atlantic Ocean.
- Tremolada, F. & Bralower, T.J. 2004. Nannofossil assemblage fluctuations during the Paleocene-Eocene Thermal Maximum at Sites 213 (Indian Ocean) and 401 (North Atlantic Ocean): palaeoceanographic implications. *Marine Micropaleontology*, **52**(1-4): 107-116.
- Tripati, A. & Elderfield, H. 2005. Deep-Sea Temperature and Circulation Changes at the Paleocene-Eocene Thermal Maximum. *Science*, **308**(5730): 1894-1898.
- Tripati, A.K. & Elderfield, H. 2004. Abrupt hydrographic changes in the equatorial Pacific and subtropical Atlantic from foraminiferal Mg/Ca indicate greenhouse origin for the thermal maximum at the Paleocene-Eocene Boundary. *Geochemistry, Geophysics, Geosystems*, **5**(2): doi:10.1029/2003GC000631.
- van Eetvelde, Y. & Dupuis, C. 2004. Upper Palaeocene and lower Eocene interval in the Dieppe-Hampshire Basin; biostratigraphic analysis based on pyritized diatoms. *In*: A.B. Beaudoin and M.J. Head (Editors) *Geological Society Special Publications 230*. Geological Society of London, London, United Kingdom, pp. 275-291.
- Westerhold, T., Röhl, U., Laskar, J., Raffi, I., Bowles, J., Lourens, L.J. & Zachos, J.C. in press. On the duration of Magnetochrons C24r and C25n, and the timing of early Eocene global warming events: Implications from the ODP Leg 208 Walvis Ridge depth transect. *Paleoceanography*.
- Wing, S.L. & Harrington, G.J. 2001. Floral response to rapid warming in the earliest Eocene and implications for concurrent faunal change. *Paleobiology*, **27**(3): 539-563.
- Wing, S.L., Bao, H. & Koch, P.L. 2000. An early Eocene cool period? Evidence for continental cooling during the warmest part of the Cenozoic. *In*: B.T. Huber, K.G. MacLeod and S.L. Wing (Editors) *Warm climates in earth history*. Cambridge University Press, Cambridge, United Kingdom.
- Wing, S.L., Harrington, G.J., Bowen, G.J. & Koch, P.L. 2003. Floral change during the Initial Eocene Thermal Maximum in the Powder River Basin, Wyoming. *In*: S.L. Wing, P.D. Gingerich, B. Schmitz and E. Thomas (Editors) *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Geological Society of America Special Paper 369, Boulder, Colorado, pp. 425-440.
- Wing, S.L., Harrington, G.J., Smith, F.A., Bloch, J.I., Boyer, D.M. & Freeman, K.H. 2005. Transient Floral Change and Rapid Global Warming at the Paleocene-Eocene Boundary. *Science*, **310**(5750): 993-996.

- Xu, W., Lowell, R.P. & Peltzer, E.T. 2001. Effect of seafloor temperature and pressure variations on methane flux from a gas hydrate layer: Comparison between current and late Paleocene climate conditions. *Journal of Geophysical Research*, **106**(26,413-26,423).
- Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**: 686-693.
- Zachos, J.C., Lohmann, K.C., Walker, J.C.G. & Wise, S.W. 1993. Abrupt climate change and transient climates during the Palaeogene: A marine perspective. *Journal of Geology*, **101**: 191-213.
- Zachos, J.C., Kroon, D., Blum, P. et al. 2004. Proceedings of the Ocean Drilling Program, Initial Reports, 208. Available from World Wide Web: http://www-odp.tamu.edu/publications/208_IR/208ir.htm.
- Zachos, J.C., Wara, M.W., Bohaty, S., Delaney, M.L., Petrizzo, M.R., Brill, A., Bralower, T.J. & Premoli Silva, I. 2003. A transient rise in tropical sea surface temperature during the Paleocene-Eocene thermal maximum. *Science*, **302**: 1151-1154.
- Zachos, J.C., Schouten, S., Bohaty, S., Quattlebaum, T., Sluijs, A., Brinkhuis, H., Gibbs, S. & 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**(9): 737-740.
- Zachos, J.C., Röhl, U., Schellenberg, S.A., Sluijs, A., Hodell, D.A., Kelly, D.C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L.J., McCarren, H. & Kroon, D. 2005. Rapid Acidification of the Ocean during the Paleocene-Eocene Thermal Maximum. *Science*, **308**(5728): 1611-1615.

Fig. 1

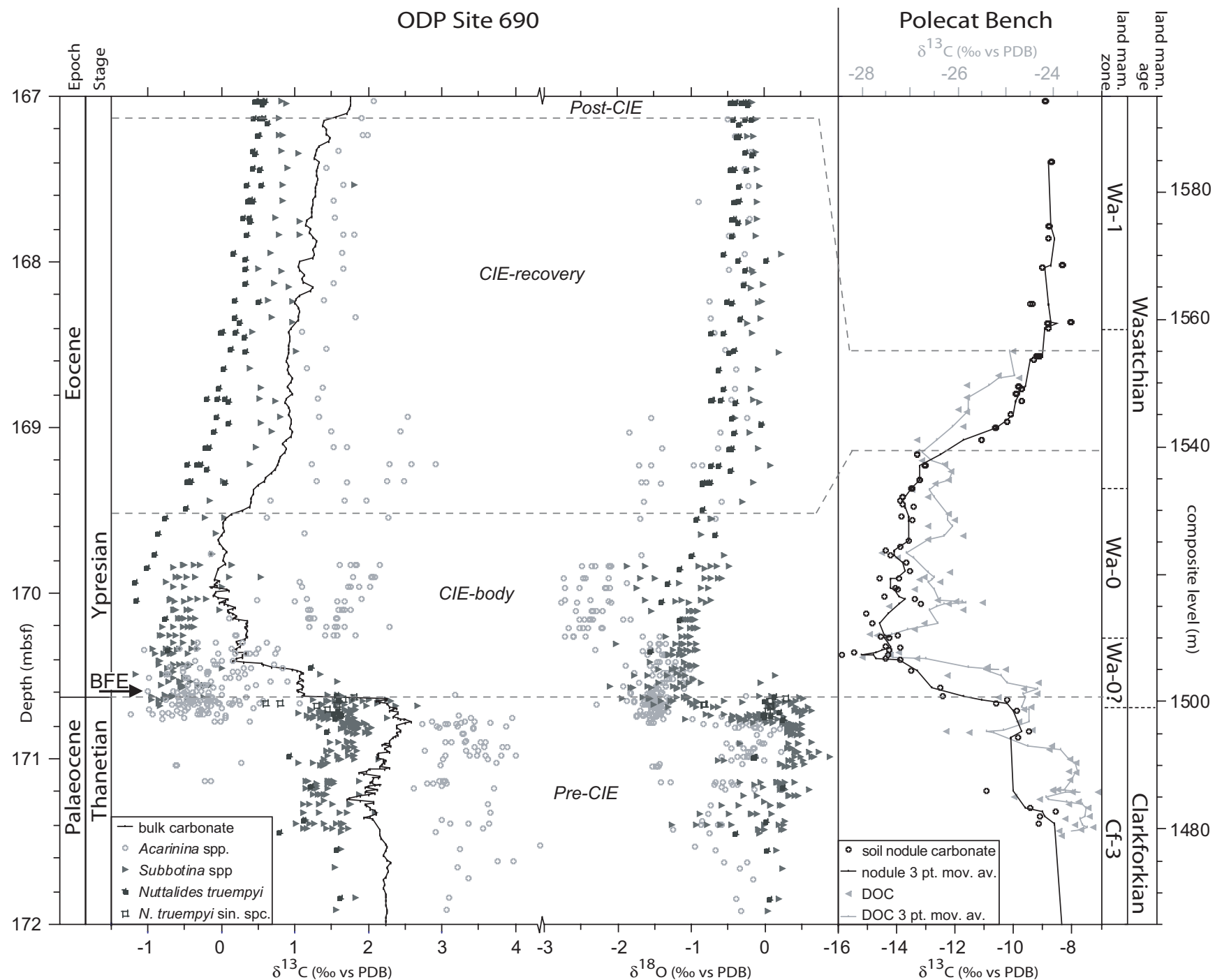


Fig. 2

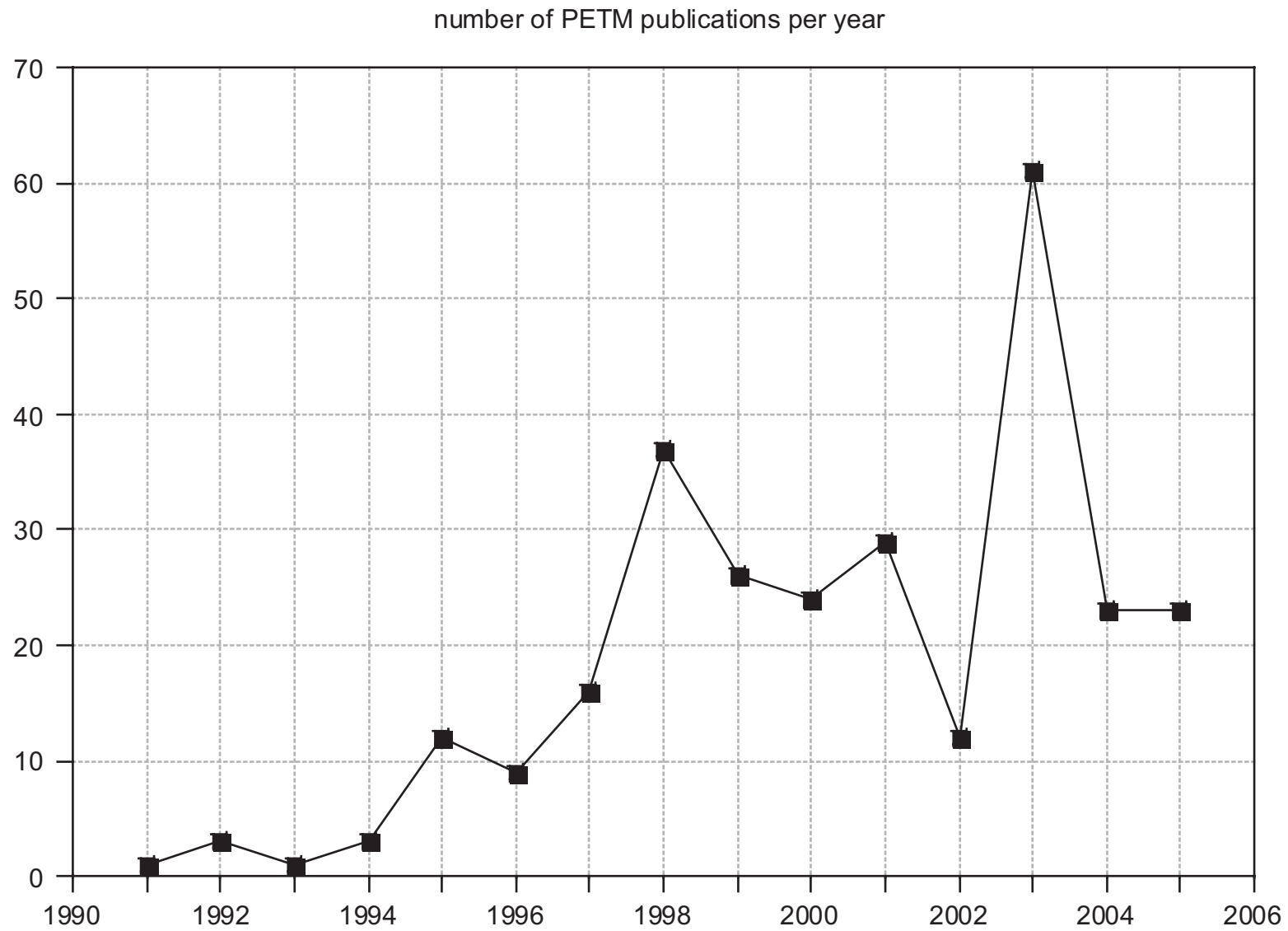
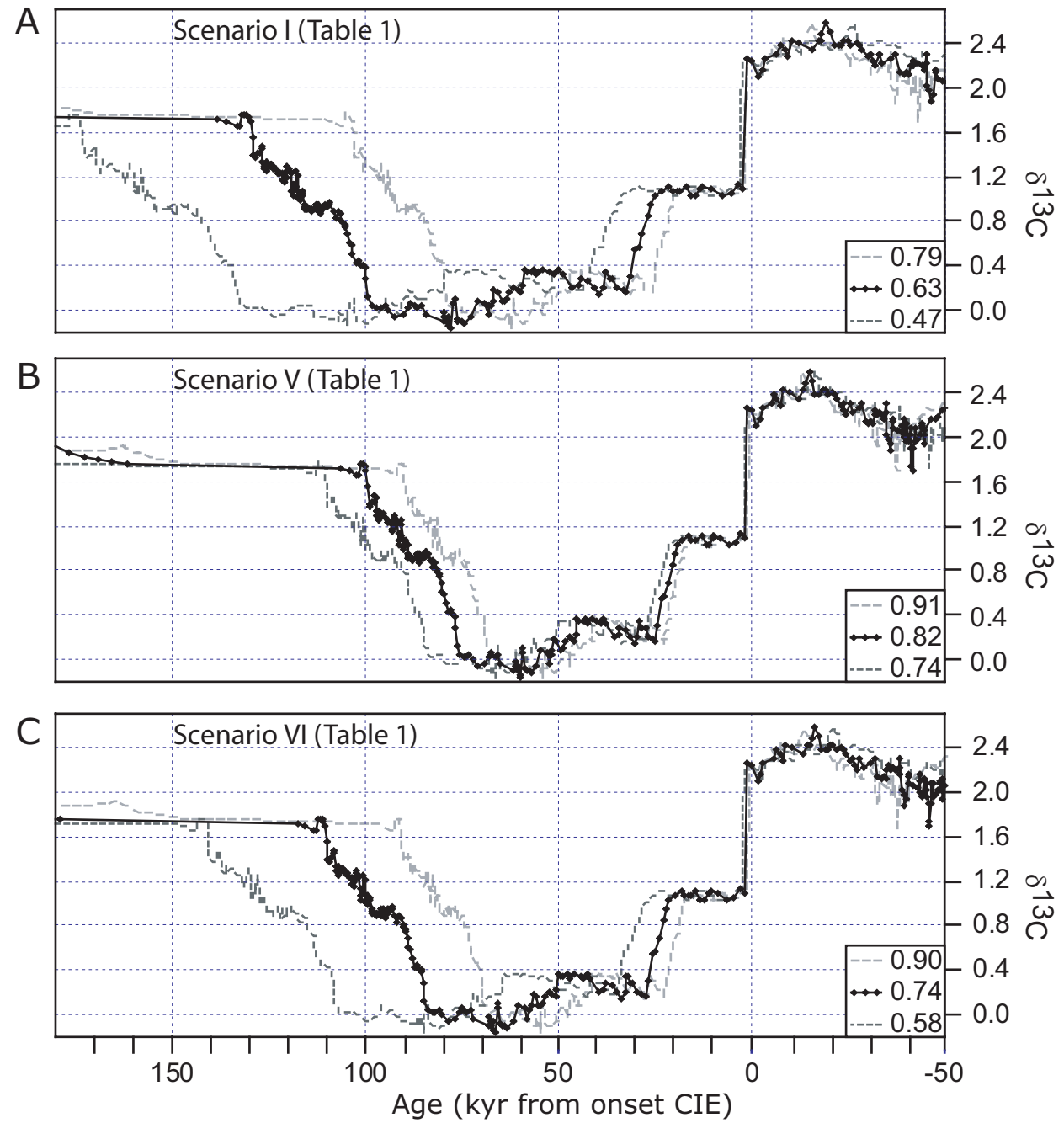


Fig. 3



a

Background ET3He flux and sedimentation rate model for Hole 690B. Expansion not included						
model (Fig. 5)	interval	duration (kyr)	thickness (cm)	sed rates (cm/kyr)		
I	C25n	504	937	1.86	cm/kyr	
				dens/(kyr/cm)=	2.48	g/kyr
				av flux	0.63	pcc/cm2/kyr
				minus stand dev	0.47	pcc/cm2/kyr
				plus stand dev	0.79	pcc/cm2/kyr
II	base 24r - ETM 2	2940	5181	1.76	cm/kyr	
				dens/(kyr/cm)=	2.35	g/kyr
				av flux	0.79	pcc/cm2/kyr
				minus stand dev	0.71	pcc/cm2/kyr
				plus stand dev	0.87	pcc/cm2/kyr
III	C25n - ETM 2	3444	6118	1.78	cm/kyr	
				dens/(kyr/cm)=	2.37	g/kyr
				av flux	0.71	pcc/cm2/kyr
				minus stand dev	0.56	
				plus stand dev	0.86	

b

Background ET3He flux and sedimentation rate model for Hole 690B. Expansion (11%) included						
	interval	duration (kyr)	thickness (cm)	sed rates (cm/kyr)		
IV	C25n	504	1003	1.99	cm/kyr	
				dens/(kyr/cm)=	2.66	g/kyr
				av flux	0.68	pcc/cm2/kyr
				minus stand dev	0.51	pcc/cm2/kyr
				plus stand dev	0.85	pcc/cm2/kyr
V	base 24r - ETM 2	3150	5809	1.84	cm/kyr	
				dens/(kyr/cm)=	2.46	g/kyr
				av flux	0.82	pcc/cm2/kyr
				minus stand dev	0.74	pcc/cm2/kyr
				plus stand dev	0.91	pcc/cm2/kyr
VI	C25n - ETM 2	3654	6812	1.86	cm/kyr	
				dens/(kyr/cm)=	2.49	g/kyr
				av flux	0.74	pcc/cm2/kyr
				minus stand dev	0.58	pcc/cm2/kyr
				plus stand dev	0.90	pcc/cm2/kyr

c

Background flux measurements	
Chron 24r	Chron 25n+r
ET3He pcc/g	ET3He pcc/g
0.28	0.30
0.35	0.23
0.35	0.19
0.31	0.36
0.39	0.21
0.33	0.24
0.33	av 0.25
av 0.33	stdev 0.06
stdev 0.03	
Chron 25 - ETM2 (all samples)	
ET3He pcc/g	
av 0.30	
stdev 0.06	
DB Density	1.34

Tab. 1

Fig. 4

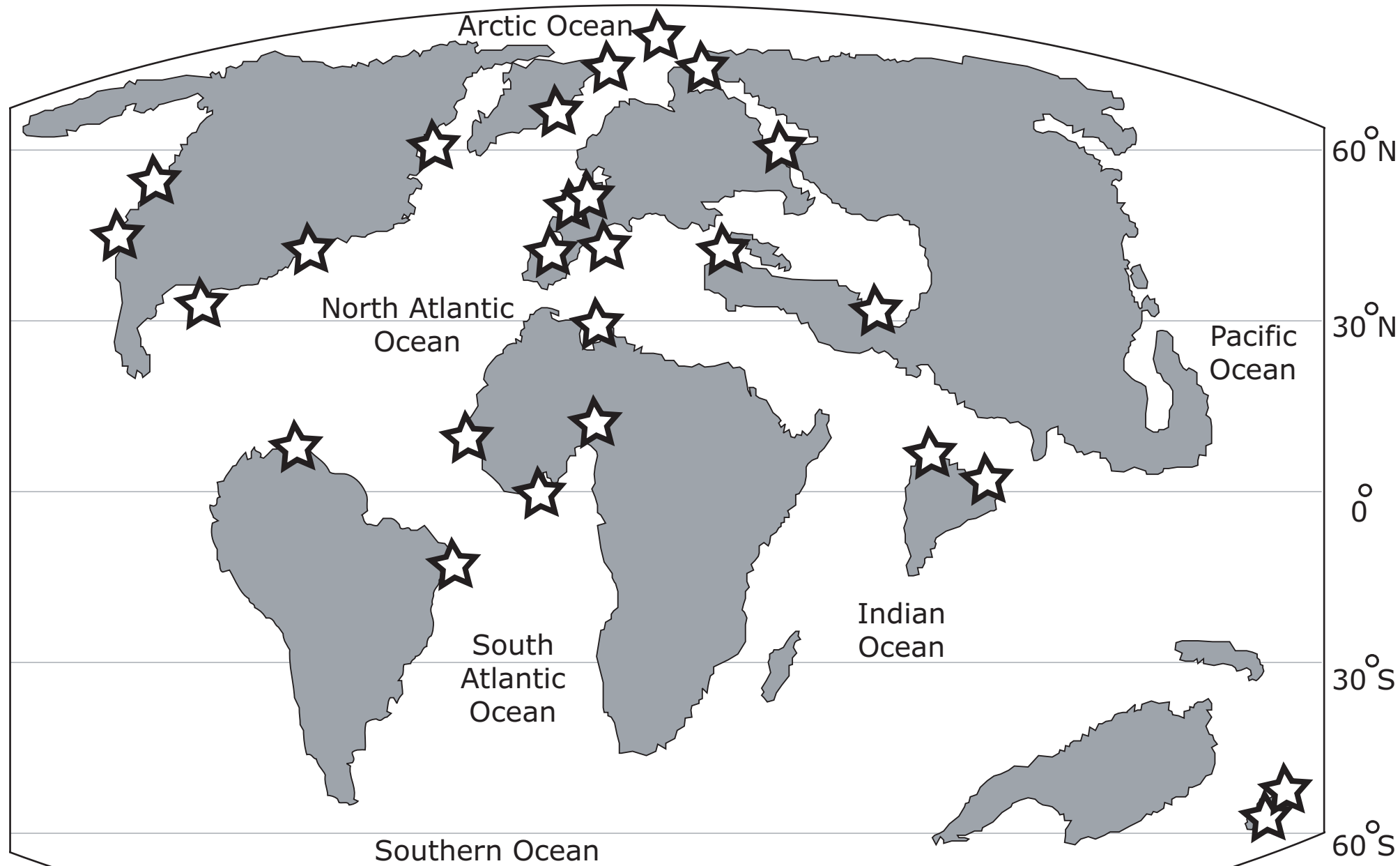
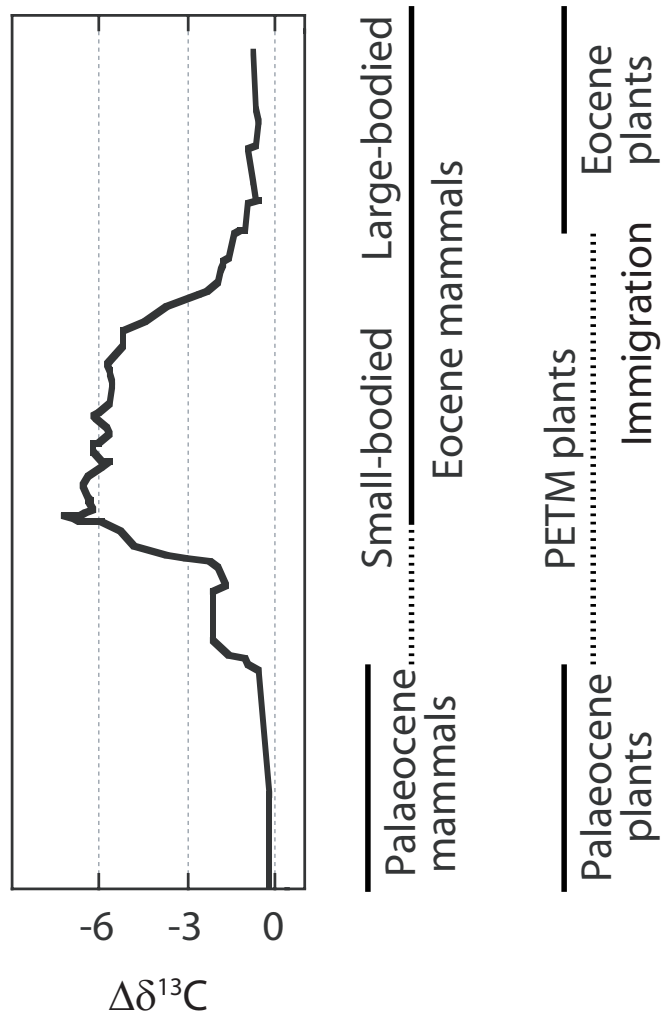


Fig. 5

A



B

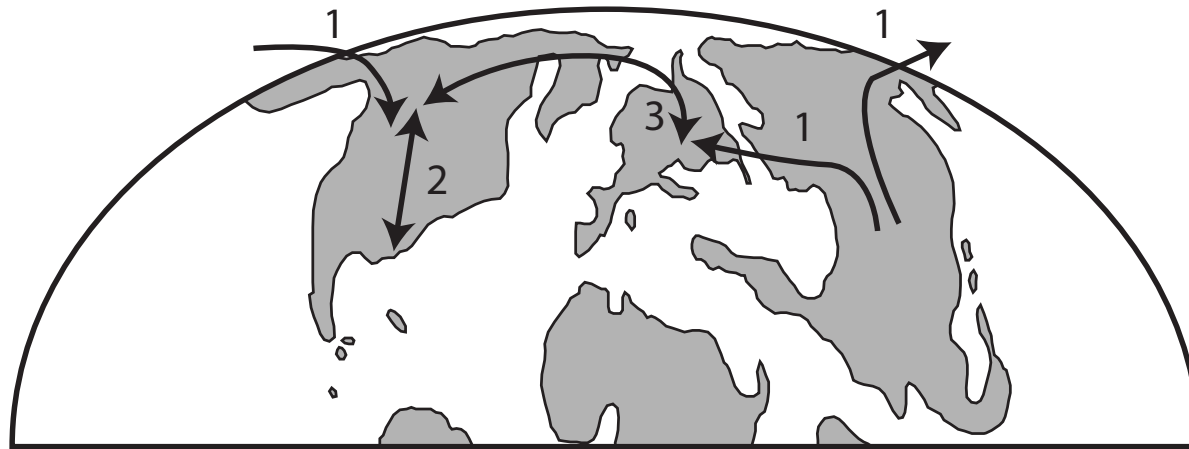


Fig. 6

