The Paleocene-Eocene thermal maximum gives insight into greenhouse gas-induced environmental and biotic change

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What happens to the Earth's climate, environment and biota when thousands of gigatons of greenhouse gas are rapidly added to the atmosphere? Modern anthropogenic forcing of atmospheric chemistry promises to provide an experiment in such change that has not been matched since the early Paleogene, when catastrophic release of carbon to the atmosphere drove abrupt, transient, hyperthermal events. Understanding of the Paleocene-Eocene Thermal Maximum (PETM, ~55 Ma), the best-documented of these events, has advanced significantly during recent years. During the PETM, carbon addition to the oceans and atmosphere of a magnitude similar to those anticipated through the 21st century. The event initiated global warming, biotic extinction and migration, and fundamental changes in the carbon and hydrological cycles that transformed the early Paleogene world. The PETM demonstrates that extreme and rapid changes in Earth Systems can be triggered by carbon cycle perturbation even in times of globally warm climate and in an ice-free world. As we describe here, an array of changes in the atmosphere, geosphere, hydrosphere, and biosphere have been documented during the PETM, and their study has provided insight into the temporal patterns and coupling of changes in the Earth Systems that accompany massive carbon release in a warm world.

Atmosphere

Atmospheric temperatures inferred from surface ocean (references in *Zachos et al.* [2005]) and terrestrial (e.g., *Wing et al.* [2005]) proxies warmed by 5 - 9° C globally during the PETM. Warming was closely associated with the release of between ~1500 and 4500 Gt of carbon to the ocean and atmosphere, resulting in large but poorly quantified increases in atmospheric CO_2 levels [*Zachos et al.*, 2005]. Atmospheric moisture transport was also impacted by the PETM as evidenced by indicators of terrestrial discharge along the continental margins (e.g., *Crouch et al.* [2003]) and isotopic records suggesting humid growing conditions across the northern mid-latitudes [*Bowen et al.*, 2004]. Floral evidence from Wyoming suggests that precipitation amounts varied there throughout the event [*Wing et al.*, 2005].

Geosphere

Carbon input to the ocean-atmosphere system during the PETM most likely came from geospheric reservoirs. The carbon source and trigger have been debated since *Dickens, et al.* [1995] proposed a methane clathrate source that was destabilized as ocean temperatures warmed from the late Paleocene to an early Eocene maximum. Alternative sources include thermogenic methane produced during the emplacement of igneous plutons in the North Atlantic seafloor [*Svensen et al.*, 2004] or widespread peat and coal burning [*Kurtz et al.*, 2003]. The geosphere played an important role in carbon sequestration during the later stages of the PETM when weathering feedbacks drove increased marine carbonate burial, buffering and ultimately leading to the recovery of the carbon cycle from the PETM [*Zachos et al.*, 2005].

Hydrosphere

One potential consequence of future global warming is a perturbation to the ocean's thermohaline circulation. Indications that ocean circulation changes occurred during the PETM are thus of great significance. Surface ocean warming was amplified at high latitudes (as much as 9° C) relative to low latitudes (5° C), while deep-water temperatures rose by 4-5° C globally (references in *Zachos et al.* [2005]). During the PETM, reduced pole-to-equator sea-surface temperature gradients or changes in continental freshwater runoff may have shifted the site of deep-water formation from a Southern Ocean locus to subtropical latitudes or to high latitudes in the northern hemisphere (e.g., *Kennett and Stott* [1991]; *Bice and Marotzke* [2002]; *Nunes and Norris* [2006]), introducing warm water to the deep sea and driving methane clathrate destabilization and further greenhouse warming [*Bice and Marotzke,* 2002].

Geographic patterns of benthic foraminifera $\delta^{13}C$ values have been used to reconstruct deep-water flow and support a circulation reversal during the PETM [*Nunes and Norris*, 2006]. Unfortunately, these data are geographically sparse, reflect water-mass characteristics of intermediate and deep-waters (from ~ 1000 m to > 3000 m paleodepth), and may have been influenced by local organic-matter regeneration. The investigated sections display varying degrees of dissolution at the onset of the PETM, resulting in time gaps that make precise site-to-site correlation difficult or impossible. Other tools for the reconstruction of deep-water circulation, including patterns of deep-sea carbonate dissolution, oxygen content and Nd isotopes are not consistent with deep ocean circulation change at the start of the PETM as inferred from $\delta^{13}C$ records (e.g., *Thomas et al.* [2003]).

Biosphere

Global environmental perturbation at the PETM is no less apparent in biotic records than in those documenting the climate or carbon cycle. Lasting changes in mammalian taxonomic composition and diversity, as well as transient body size reductions, were associated with dispersal of terrestrial mammals among the Northern Hemisphere continents at the beginning of the PETM (e.g., *Clyde and Gingerich* [1998]). PETM floras in mid-latitudes document northward range extensions of hundreds to thousands of kilometers and intercontinental dispersal [*Wing et al.*, 2005]. Marine communities exhibited a complex array of responses, ranging from the loss of ~35 - 50% of deep sea benthic foraminiferal species, the most severe extinction in the last 90 Ma (e.g., *Thomas* [1998]), to significant but transient assemblage changes in other groups, including global dominance of the warm-water dinoflagellate *Apectodinium* (e.g., *Crouch et al.* [2003]), rapid diversification of planktonic foraminifera [*Kelly et al.*, 1998], and shifts in trophic strategies of nannoplankton in shelf and open ocean locations. Overall rates and geographic patterns of terrestrial and marine ecosystem productivity appear to have varied substantially through the PETM [*Bowen et al.*, 2004; *Thomas*, 1998].

A synthesis PETM Earth Systems evolution (Fig. 1)

Phase I - Initiation. Carbon isotope records documenting global $\delta^{13}C$ decreases during the first ~15 to 30 Kyr of the PETM indicate one or more rapid (i.e. occurring within 1 - 2 Kyr) releases of ^{13}C-depleted carbon to the atmosphere-ocean system. What triggered the PETM carbon release(s) remains a critical question. In considering the PETM as a potential analogue to modern global change, it is particularly important to understand whether the PETM was initiated as a feedback (i.e. as climate crossed a warming threshold) or an externally forced event. If the PETM carbon release was a feedback, it implies that human-induced warming may also trigger a cascade of amplifying carbon cycle feedbacks. If the PETM carbon release was forced externally it might be better considered analogous to anthropogenic carbon release itself. Although no clear consensus exists in this matter, the suggestion that multiple PETM-like events may have occurred in phase with orbital cycles potentially falsifies hypotheses linking the PETM to singular forcing factors such as bolide impacts or volcanic events [*Lourens et al.*, 2005]. Whatever the trigger, the onset of the PETM was characterized by abrupt changes spanning the Earth Systems, including the acidification of the oceans, rapid changes in terrestrial and marine biota, and extinction of benthic foraminifera. The linkages between carbon cycle perturbation and synchronous biotic change are not completely understood: individual ecosystems may have responded directly to such aspects of environmental change as carbon addition (ocean acidification, elevated pCO_2) and/or indirectly to consequences of carbon release (e.g., rising temperatures, increased precipitation, changes in nutrient supply and/or distribution).

Phase II – Alternate semi-stable state. A distinct, ~60 Kyr, interval beginning when $\delta^{13}C$ values reached their minimum has been called the "body" of the PETM and is characterized by continued increases in global temperature, low and relatively stable oceanic and terrestrial $\delta^{13}C$ values, increased $\delta^{13}C$ offsets between terrestrial and marine systems, slow dilution of oceanic acidity, and biotic assemblages (dinoflagellate cysts, benthic and planktonic foraminifera, and calcareous nannoplankton in the oceans; plants and mammals on the continents) that include transient, often unique taxa. The body of the PETM demonstrates that the Earth Systems response to initial PETM forcing was not simply a shift away from, and recovery to, equilibrium, but a shift to a fundamentally different, semi-stable state [*Bowen et al.*, 2004]. This state may in some ways represent our global environmental future, and it is therefore critical that we begin to characterize it. *Bowen et al.* [2004] proposed a model suggesting substantial terrestrial ecosystem change during the body of the PETM, but focused study of this interval has just begun. Low $\delta^{13}C$ values are one unexplained and characteristic feature of the PETM body. We suggest the stable isotopic values reflect temporary stagnation of components of the carbon cycle during a time of poor seafloor carbonate preservation [*Zachos et al.*, 2005] and reduced open-ocean carbonate export production [*Thomas*, 1998]. If so, the continued rise of global temperatures and ecosystem change during the body of the PETM may represent changes associated with a long-term lag in carbon cycle recovery from massive carbon release, and may be indicative of patterns of future global change.

Phase III – Recovery. Over the final ~70 Kyr of the PETM Earth's systems recovered to an earliest Eocene state that was in many ways similar to the late Paleocene. The details of the recovery process are relevant to understanding how Earth's Systems recover from carbon cycle perturbation and the degree to which such events lead to lasting changes in Earth's climate, biota, and geochemical systems. Recovery included dramatic increases in seafloor carbonate burial rates, falling global temperatures, and a transition from distinctive PETM biotic assemblages to those typical of the early Eocene. Elevated marine carbonate burial represents a potential mechanism for 'righting' the carbon cycle following massive carbon release, but given the intervening 60 Kyr of low carbonate burial during the PETM body it is important to understand how this process proceeded. The biotic record provides the strongest evidence for lasting change induced by the PETM. Earliest Eocene communities of terrestrial mammals and benthic foraminifera differ widely from their latest Paleocene counterparts in species composition and ecological features. These differences may reflect permanent environmental change, interactions among organisms brought together by range changes, or the irreversibility of evolution and extinction.

Fifteen years of study have revealed the PETM as a case study of the broad impacts of massive carbon cycle perturbation during a time of globally warm climate. Continued study promises not only to guide our understanding of global change mechanisms during the PETM, but to illustrate modes of connectivity among Earth's Systems and patterns of change that may characterize Earth's future.

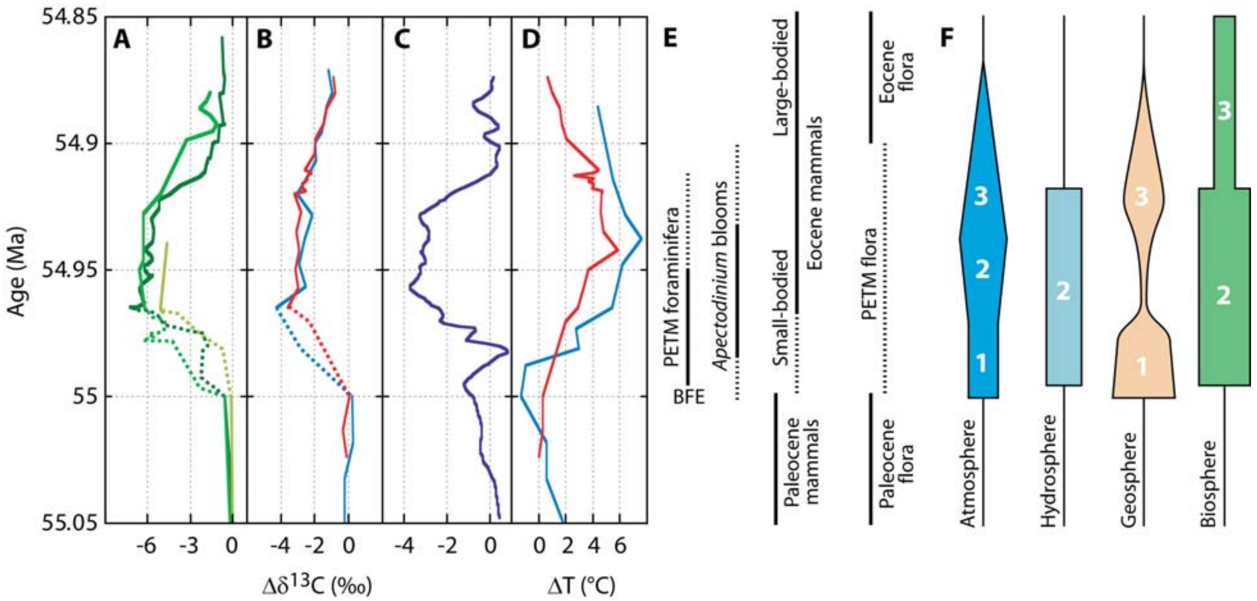

Figure 1: Environmental records and a 3-phase model of Earth Systems evolution through the Paleocene-Eocene Thermal Maximum (PETM, age model following *Bowen et al.*[2004]). **A** & **B)** Carbon isotope records of the PETM given as anomalies relative to the interval 55.05 – 55.00 Ma. Terrestrial paleosol carbonate records (**A**) from northern Wyoming (dark green) northern Spain (light green), and southern China (olive green). Marine planktonic foraminifera records (**B**) from the subtropical Pacific (red) and southern Atlantic (blue). Carbon isotope changes during the onset of the PETM (dashed lines) occurred as a series of abrupt (~1 Kyr) steps that are not clearly resolved in these records. **C)** Difference of the averaged δ^{13}C curves for the 3 terrestrial and 2 surface ocean records. **D)** Surface temperature anomaly records for the 2 oceanic sites, with colors as in **B**. All data in **A** – **D** compiled by *Bowen et al.* [2004]. **E)** Simplified patterns of biotic change through the PETM, compiled from a number of sources (including *Kennett and Stott* [1991]; *Thomas* [1998]; *Crouch et al.* [2003]; *Wing et al.* [2005]). BFE = Benthic foraminiferal extinction. **F)** A synthesis of global change associated with the PETM. Width of bars correspond to severity of change relative to late Paleocene conditions. 1 = Initiation of the PETM: intrinsic or extrinsic trigger; carbon release from geospheric reservoirs to the ocean/atmosphere; buildup of carbon-based greenhouse gases in the atmosphere; ocean acidification and dissolution of seafloor carbonate sediments, benthic foraminiferal extinction, intercontinental mammal migration. 2 = Body of

the PETM: low marine carbonate burial rates; altered hydrologic cycle; distinctive PETM biotic communities; gradual climatic warming. 3 = Recovery interval: rapid burial of carbon in marine carbonate sediments; climate cooling; restructured biotic communities persist into the Early Eocene.

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