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A critical evaluation of the Paleocene–Eocene Thermal Maximum: an example of things to come?

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Abstract

The Paleocene–Eocene Thermal Maximum (PETM), arguably the most dramatic hyperthermal event recorded to date, occurred approximately 55 million years ago (Ma). During this event thousands of petagrams of carbon were released into the atmosphere and hydrosphere affecting the climate, ocean chemistry and marine and terrestrial ecosystems. With a duration of approximately 100,000 years (though possibly as long as 170,000 years) and global temperature increases of between 4-8°C, terrestrial and marine faunal turnover occurred including mammalian dispersal, rapid evolutionary and ecological change and transient diversification. The PETM, therefore, offers a valuable insight into shifts in the climate regime and the resultant marine and biotic response that may be relevant to future anthropogenically induced climate change. The mechanisms for delivery of isotopically light carbon into the atmosphere and hydrosphere remain a hotly debated topic. Here we discuss numerous possible sources of carbon and the mechanisms responsible for their release.

Keywords: PETM, Hyperthermal Events, Climate change, Mechanisms for PETM, Sources of Carbon, Atmospheric pCO_2

Introduction

With extreme climatic events dominating the news with dire warnings of potential disruption and displacement of global populations it has become vital to understand global response to anthropogenic climate change. It has been observed that global surface temperatures have increased by 0.74°C in a linear trend since instrumental records began in 1850 (IPCC 2012). While anthropogenic carbon release comes through burning fossil fuels the sources of carbon for the PETM and the mechanisms for their release has been the subject of fierce debate amongst palaeoclimateologists.

Lovell (2010) has suggested that since the start of the industrial revolution, a mere 200 years ago, we have released approximately one third of the amount of carbon released during the 10,000 year onset of the PETM. During the PETM an increase in global temperatures of 5°C over a 10,000 year period requires a vast input of carbon with between 1500 and 55,000PgC being injected into the atmosphere alone (Pagani *et al.,* 2006). Maintaining this concentration for tens of thousands of years implies a partial equilibration with the carbonate system in the oceans leading to a total release of carbon of between 5400 and 112,000Pg (Pagani *et al.,* 2006).

Characterisation

The PETM marks a sudden and dramatic increase in average global temperatures of between 4°C and 8°C (Kennett and Scott, 1991) and lasted for between 100,000 and 170,000 years (Rohl *et al.,* 2000, 2007; Farley and Eltgroth, 2003; Aziz *et al.,* 2008; Giusberti *et al.,* 2008). The PETM is defined by a negative carbon isotope excursion (CIE) recorded globally in both the marine and terrestrial realms. There is however a difference in magnitude of the CIE between the two realms with marine carbonates consistently recording a lower magnitude CIE than the terrestrial realm. Marine carbonates typically record a $\delta^{13}C$ shift of between 2.5‰ and 4‰ (Kennett and Scott, 1991; Bains *et al.,* 1999; Thomas *et al.,* 2002; Zachos *et al.,* 2003; Tripani and Elderfield, 2005) while terrestrial plants and carbonate nodules usually record a $\delta^{13}C$ shift of greater than 5‰, (Koch *et al.,* 1992, 2003; Bowen *et al.,* 2001, 2002; Schmitz and Pujalte, 2003, 2007).

The CIE associated with the PETM was first identified by Stott *et al.* (1990) at Ocean Drilling Program (ODP) Site 690 in the Antarctic Ocean through the analysis of foraminiferal carbon isotope variation though the Paleocene–Eocene transition. The PETM encompasses three distinct phases (Bowen and Zachos, 2010) ; an initial abrupt negative CIE, a phase of $\delta^{13}C$ stability (Carbon Isotope Stability Period, CISP) and finally a recovery phase where $\delta^{13}C$ values return to pre-CIE levels. The classic profile for the PETM shows a rapid CIE of approximately –2.5‰ in the marine realm and approximately –6‰ in the terrestrial realm (Bowen and Zachos, 2010). This discrepancy in the CIE magnitude is believed to be mainly due to the increased fractionation of CO_2 by flora due to increased precipitation through the PETM (Bowen *et al.,* 2004). Following the rapid negative CIE a relatively short period of carbon isotope stability occurs before a gradual carbon isotope recovery phase as carbon isotope values return to pre-PETM levels due to the slow drawdown of atmospheric CO_2 by chemical weathering of silicate rocks (Dickens *et al.,* 1995). An alternative to this classic profile has been presented by Bowen and Zachos (2010) in which, following the rapid negative CIE, there is a much longer period of carbon isotope stability followed by a rapid recovery phase returning to pre-PETM carbon isotope values. This rapid drawdown of CO_2 is believed to be the result of a rapid floral bloom (Bowen and Zachos, 2010).

The CIE itself is associated with the relocation of oceanic deep water formation, a decrease in the thermal gradients between the polar and equatorial regions, a decrease in the thermal gradient between surface and bottom waters, and increasing acidification of the oceans giving rise to the mass extinction of foraminifera and changes in the palaeofauna (Kennet and Scott, 1991; Thomas, 1998; Wing *et al.,* 2005; Zachos *et al.,* 2005; Zeebe *et al.,* 2008) making this an important event to understand further.

Impact upon biota

Numerous abrupt changes occurred globally which are coincident with the onset of the PETM including the acidification of the oceans and rapid changes in terrestrial and marine biota. Deep sea benthic foraminifera experienced their greatest extinction of the past 90 million years (Thomas, 1990, 1998; Kennett and Stott, 1991; Speijer *et al.,* 1996; Thomas and Shackleton, 1996) culminating in the loss of 30%–50% of species present during the Cenozoic (Schmitz *et al.,* 1997; Alegret and Ortiz, 2006; Alegret *et al.,* 2009). Other major biological changes include a rapid evolutionary turnover of planktic foraminifera and calcareous nannoplankton, which experienced transient diversifications (Kelly *et al.,* 1996; Aubrey, 1998; Monechi *et al.,* 2000; Kelly, 2002; Raffi *et al.,* 2005; Gibbs *et al.,* 2006). In addition to this *Apectodinium* dinoflagellates bloomed worldwide in shelf areas and migrated from equatorial regions to high latitude locations (Crouch *et al.,* 2001; Figure 1). This turnover of marine biota also affected the deep marine environments leading to a Benthic Extinction Event (BEE) (Orue-Etxebarria *et al.,* 2001) and was accompanied by diversification at a species level, as well as a considerable increase in shell sizes and adult diamorphism that has been interpreted as adaptation to the changed environmental conditions (Hottinger, 1998).

The rapid extinction of 18% of smaller benthic foraminifera also occurs at the onset of the CIE following an initial ocean warming event which is inferred through calcareous nannofossil records during the final 46,000 years of the Paleocene (Alegret *et al.,* 2009). These extinctions increased to a peak approximately 10,000 years after the onset of the CIE with the BEE affecting 37% of species. In total 55% of the benthic foraminiferal species became extinct due to the PETM (Schmitz *et al.,* 1997; Alegret and Ortiz, 2006; Alegret *et al.,* 2009). As this extinction event took place under inferred oxic conditions without evidence for carbonate dissolution at shallow depths (Alegret *et al.*, 2009) this suggests that increased ocean acidity and deoxygenation of bottom waters was not the main cause of this extinction.

On land, archaic mammals were replaced by modern groups, including the earliest true primates (Figure 1; Clyde and Gingerich, 1998; Bowen *et al.,* 2002; Gingerich, 2003; Smith *et al.,* 2006), whilst floras underwent important changes including increased diversity, leaf size, and shape, migration of equatorial plants to higher latitudes and a rapid transition from a mixed angiosperm/gymnosperm flora to a purely angiosperm flora (Wing *et al.,* 2005; Jaramillo, 2006)

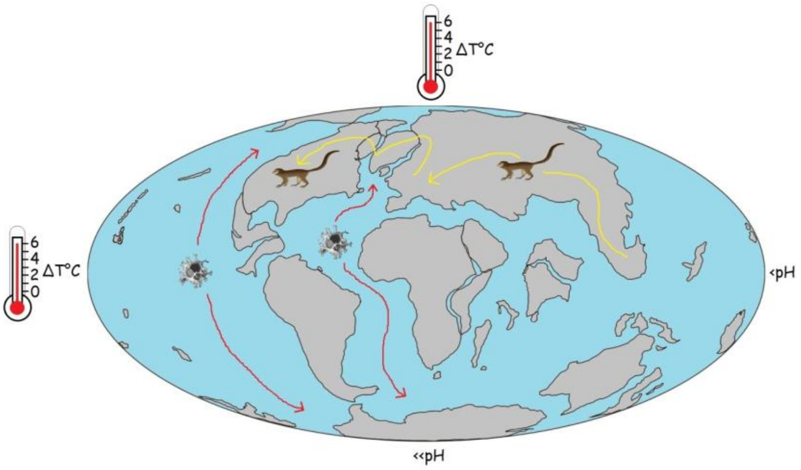

Figure 1: Cartoon representation of the impact the Paleocene – Eocene Thermal Maximum (PETM) had upon flora and fauna. In the marine realm Apectodinium dinoflagellates migrates to higher latitudes (Red arrow). In the terrestrial realm the first true primate migrate from China through to Europe and into North America (Yellow arrow). As indicated through the thermometers a decrease in the thermal gradient between polar regions and equatorial regions occurs with a greater temperature increases located in polar regions. An increase in ocean acidity with greater acidification affecting polar waters is represented through decreasing pH markers. See text for references. Palaeogeographic map redrawn from palaeomap http://www.odsn.deodsnoutfiles21674hr.jpg

Cause of the PETM

A synopsis of mechanisms that have been proposed for the cause of the PETM can be seen in Figure 2 and Table 1. The characteristic negative CIE associated with

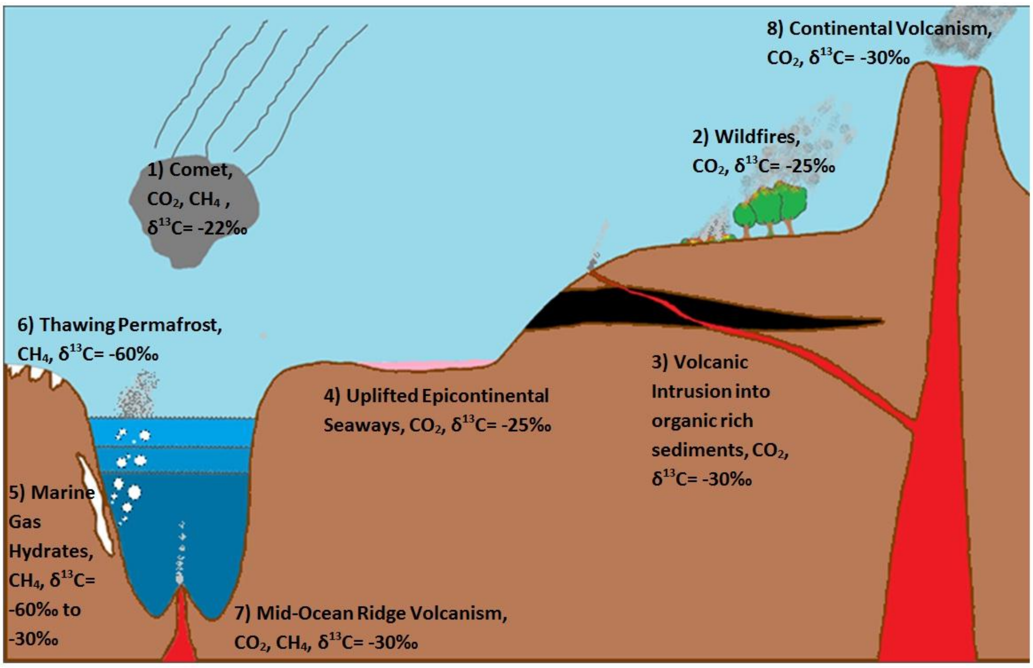

Figure 2: A cartoon detailing the possible sources of carbon that would have been released at the start of the Paleocene – Eocene Thermal Maximum (PETM) (see text for further explanation and references). 1. Cometary impact. 2. Wild fires. 3. Volcanic intrusion through organic rich mudrock. 4. Uplift of epicontinental seaways. 5. Destabilization of marine gas hydrates. 6. Thawing permafrost. 7. Mid-Ocean Ridge volcanism. 8. Continental volcanism.

Table 1: Table 2 Various sources and mechanisms for the release of isotopically light carbon believed to be responsible for the carbon isotope excursion associated with the Paleocene – Eocene Thermal Maximum.

Mechanism for carbon destabilisation	Source of light carbon	Gasses released	$\delta^{13}C$ ‰ of carbon	Reference
Comet Impact	Mantle	CO_2, CH_4	-22‰	Kent *et al.* (2003); Cramer and Kent (2005)
	Comet	CO_2, CH_4		
	Marine gas hydrates	CH_4		
Burning organics	Vegetation	CO_2	-22‰	Kurtz *et al.* (2003)
	Peat	CO_2		
	Coal	CO_2		
Uplift of Epicontinental Seaways through Magmatism or Tectonics	Oxidation of organics	CO_2	-25‰	Higgins and Schrag (2006)
	Aerobic respiration	CO_2		
Intense Flood Basalt Magmatism or Volcanism	Mantle	CO_2	-30‰	Storey *et al.* (2007)
	Organic mudstones	CO_2, CH_4		
	Mid Ocean Ridge	CO_2		
Clathrate Destabilisation				
Changing ocean circulation patterns	Marine gas hydrates	CH_4	-60‰ to -40‰	Dickens (1995)
Sea Level fall through tectonic uplift	Marine gas hydrates	CH_4		
Slope failure	Marine gas hydrates	CH_4		
Initial increasing temperatures	Thawing Permafrost	CO_2	~-60‰	DeConto *et al.* (2012)

the PETM is intrinsically linked with the release of isotopically light carbon into the atmosphere for which many mechanisms and sources have been suggested. As proposed by Kent *et al.* (2003) the impact of an asteroid or comet with the Earth is a valid mechanism for the destabilisation of light carbon through numerous sources. Such sources include ^{13}C derived from the mantle, which is released as a result of the impact, or derived from the comet itself, which is released upon impact or through the destabilisation of frozen methane gas hydrates buried at depth under the seafloor. Whilst the media and popular science magazines often support such catastrophic causes for major climate events, and the mass extinctions associated with them, further investigations have failed to identify a suitably sized crater dated to the event. Also the presence of magnetic nanoparticles found by Kent *et al.* (2003) and interpreted by them to have formed during the impact of a comet may in fact have a biological origin (Kopp *et al., 2007;* Lippert and Zachos, 2007)

Kurtz *et al.* (2003) suggested that wildfires on the African continent could be a mechanism for the release of light carbon stored in vegetation such as peat and coal. However, for this mechanism to be valid the scale of such fires would have to be on such a huge scale that remnants of them should be discernible within the sedimentary deposits off the West African coast (Moore and Kurtz, 2008). Evidence of such an event would be discernible in the form of an increase in graphite black carbon (GBC). No increase in GBC was found at the onset of the CIE (Moore and Kurtz, 2008).

Storey *et al.* (2007) invoked the thermogenic release of isotopically light carbon through volcanic intrusion into mudstones rich in organic matter as a mechanism for the generation of the CIE associated with the PETM. Furthermore, they also suggested that this could have been supplemented by the release of mantle derived light carbon through intense magmatism at the Mid Atlantic Ridge. A problem with this hypothesis is that it relies upon a one off mechanism and is unlikely to be sufficient to increase global temperatures to the values seen through the PETM.

Higgins and Schrag (2006) proposed that the uplift of epicontinental seaways induced through either magmatism or tectonic processes could release isotopically light carbon via the oxidation and bacterial respiration of the aerated organic matter. While numerous epicontinental seaways were viable prospects for uplift at this time, including large parts of Africa-Arabia and Eurasia (Reyment, 1980; Akhmetiev and Beniamovski, 2004), it is as unlikely mechanism as such events are known to have happened previously without large scale release of light carbon. One such event was the Messinian Salinity Crisis during which the Mediterranean Sea evaporated through tectonic response rather than eustatic response with no CIE recorded in association with this event (Shackleton and Hall, 1997; Hodell *et al.,* 2001; Billups 2002; Bickert *et al.,* 2004).

It is widely accepted that the most likely source for the carbon associated with the PETM is the release of isotopically light methane from the dissociation of sea floor gas hydrates. This is due to the extremely negative $\delta^{13}C$ value of marine gas hydrates (Dickens *et al.,* 1995). While the source for carbon is relatively well constrained the mechanism for the release of this methane remains debated. Numerous mechanisms have been proposed for destabilisation of these marine gas hydrates including changes in ocean circulation patterns (Nunes and Norris, 2006).

This change is believed to have been brought about as a result of a gradual increase in seawater temperatures (Zachos *et al.,* 2003). The cause of this gradual increase in temperature is uncertain but could be related to volcanic activity happening around this time (Zachos *et al.,* 2003)

Sea level fall through tectonic uplift in the proto-North Atlantic Ocean was proposed by MacLennan and Jones (2006) as a mechanism for destabilizing marine gas hydrates. However, sea level fall through tectonic uplift would have needed to be sudden and dramatic as warming through the late Paleocene would allow for thermal expansion of the oceans globally creating a net rise in sea level. A further prospective mechanism for marine gas hydrate destabilisation was proposed by Katz *et al.* (2001) through seismic imaging off the east coast of the United States. This work showed slope failure along the continental shelf, which could have resulted in the release of the marine gas hydrates.

More recently DeConto *et al.* (2012), following analysis of sediments near Gubbio, Italy, discussed the likelihood that thawing permafrost in the high latitudes including Antarctica, could have released enough methane to have caused the CIE associated with the PETM.

Whatever the cause of the PETM it is unlikely that a single source of carbon release could have initiated the PETM. Pagani *et al.* (2006) argued that marine gas hydrates could only give rise to a CIE of around –6‰ if the climate sensitivity to CO_2 in the Paleocene was much greater than it is currently assumed to be.

Conclusion

The PETM is the best analogue in the Cenozoic for the interpretation of climate change in the near future. Lovell (2010) has suggested that anthropogenic carbon release over the past 200 years equates to approximately one third of total carbon released during the 10,000 year onset of the PETM making the understanding of this event of vital importance.

The sources of carbon and the mechanisms for their release remain topical. Whilst it is unlikely that a sole cause is responsible for the PETM it seems very favourable that the dissociation of marine gas hydrates played a primary role. The reason for this is that marine gas hydrates have very negative isotopic values, and as such less carbon is required to have been released to cause the isotope shift associated with the PETM.

However, while the dissociation of marine gas hydrates remains a primary contender for the cause of the CIE, the recent work of DeConto *et al.* (2012) into the release of carbon through thawing of permafrost within the Arctic and Antarctic region seems to be a very plausible mechanism, requiring further investigation. The potential of high latitude climatic forcing to trigger the release of large quantities of carbon, initiating positive warming feedback, may be the key to unlocking the PETM.

Whilst anthropogenic climate change is not currently believed to be caused by the destabilization of marine gas hydrates or through thawing permafrost it is possible that as the planet warms these vast reserves of carbon in oceans and the Arctic tundra may be released there by exacerbating the problem for mankind.

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