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Do the large carbon isotopic excursions in terrestrial organic matter across Paleocene–Eocene boundary in India indicate intensification of tropical precipitation?

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ABSTRACT

Five distinct transient warming (hyperthermal) events (Paleocene–Eocene Thermal Maximum [PETM], H1/ETM2/ELMO, H2, I1, and I2), marked by negative carbon isotope excursions (CIEs) occurred between Late Paleocene and Early Eocene (~56 to 52 Ma) interval. However, not many records of either the PETM or definitive Early Eocene Hyperthermals (EEHs) are yet available from terrestrial realm in the tropics except two neo-tropical sections of Colombia and Venezuela (Jaramillo et al., 2010). Therefore, response of the tropical biosphere to these warming events is not very well known. Here we report high resolution carbon isotope ($\delta^{13}C$) chemostratigraphy, biomarker, calcareous nannofossils, and pollen data from the Cambay shale Formation of Western India (paleolatitude ~ 5°S), which show complete preservation of all the above CIE events including the PETM, hitherto unknown from tropical terrestrial record. Comparatively larger magnitudes of CIEs for all the hyperthermal events (the PETM and EEHs) point towards a possible intensification of precipitation during the PETM and all the early Eocene hyperthermal/CIE events. This inference is supported by data of lignin phenols and presence of tropical rain forest elements spanning the entire time period ~56–52 Ma and suggest that higher organic burial and soil erosion favored deposition of thick lignitic seams as a consequence of high tropical precipitation.

1. Introduction

Earth's surface experienced a series of transient warming/hyperthermal events superimposed on the long term warming trend from Late Paleocene (~56 Ma) to the Early Eocene (~52 Ma) and are marked by negative Carbon Isotopic ($\delta^{13}C$) Excursions (CIEs) in various proxy records (Zachos et al., 2010). Short lives (ranging between 50 and 200 kyr) of these CIEs/hyperhtermals indicate both rapid addition of ^{13}C depleted carbon to the long-term carbon cycle as well as rapid burial of ^{13}C depleted organic matter (Bowen and Zachos, 2010) during these episodes e.g., Paleocene–Eocene Thermal Maximum (PETM) or Early Eocene Thermal Maxima 1 (ETM1), (ETM2) or H1, H2, I1, and I2 (Dickens et al., 1995, 1997). Considered as a past analog of future greenhouse earth with ongoing rapid addition of ^{13}C depleted carbon from fossil fuel burning decades of research on these paleo-hyperthermals mainly focused on understanding both the mechanisms and consequences of these events. Characterized by global surface temperature rise of ~5 to 9 °C (McInerney and Wing, 2011) the PETM was the most prominent among these hyperthermals. Newly discovered Early Eocene Hyperthermal events (EEHs) i.e., H1, H2, I1, and I2 have received less attention compared to the PETM. One of the most distinctive features of the PETM is ~2 to 7‰ negative CIE both in atmosphere–ocean system denoting addition of >2000 Gt of ^{13}C depleted carbon to the long-term carbon cycle (Dickens et al., 1995; Dickens et al., 1997). However, the magnitude of these CIEs varies depending on the carbon phase analyzed, paleo-latitudinal location, and the completeness of the sedimentary record (Bowen et al., 2006; Sluijs et al., 2007; Sluijs and Dickens, 2012). In case of the PETM, magnitude of the negative CIE is typically 2 to 4‰ in marine carbonate (benthic and planktic foraminifera; Kennett and Stott, 1991; Thomas and Shackleton, 1996) while it is 4 to 5‰ in bulk terrestrial organic carbon (Domingo et al., 2009), and ~6‰ in soil carbonate (Koch et al., 1992). Similar to the PETM, magnitude of the negative CIE of

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the ETM2/H1 in marine calcareous microfossils and bulk organic matter varies from ~1 to 1.5‰ (Stap et al., 2010) and ~3 to 3.5‰ (Sluijs et al., 2009; Clementz et al., 2011) respectively. The magnitude of the negative CIE of the H2 and other two hyperthermals (I1 and I2) in high resolution marine carbonate varies from 0.2 to 0.7‰ (Stap et al., 2010), ~0.5 to 0.7‰, and ~0.2 to 0.6‰ (Nicolo et al., 2007) respectively. However, with addition of new data, obtained from different carbon phases, magnitude of these hyperthermals may change in future, as it happened for the PETM. Since the magnitude of the CIEs is very crucial to quantify the amount of carbon added to the long-term carbon cycle (Sluijs et al., 2007; Sluijs and Dickens, 2012) and consequent climate changes, the large spread in the reported magnitude for the CIEs invited several conflicting opinions regarding the temperature and precipitation change across these CIEs (Zeebe et al., 2009; Diefendorfa et al., 2010). For example, ocean acidification at the onset of the PETM leads to dissolution of previously deposited marine carbonate while prohibiting deposition of new carbonates. Thus marine carbonate fails to record the real depletion in ^{13}C at the PETM onset which has the largest isotopic shift. Hence, marine carbonate many a times underestimates the magnitude of the negative CIEs (Zachos et al., 2005). Further, decreased pH during ocean acidification reduces the CO_3^{2-} concentration thereby enriching the $\delta^{13}C$ of marine fossil carbonates (Spero et al., 1997; Uchikawa and Zeebe, 2010). Soil carbonate records, on the other hand, are thought to overestimate the CIEs influenced either by vegetation change (Smith et al., 2007) or by change in soil respiration rate in an elevated atmospheric CO_2 and increased precipitation regime (Bowen et al., 2004). Bulk organic matter data are expected either to amplify or dampen the signal depending on the depositional environment and response of the biosphere with the warming (Sluijs and Dickens, 2012). While mixing of marine and terrestrial organic matter in marginal marine sections and change in water use efficiency (WUE) of the plant in a changed climate may either dampen or amplify the signal, plant community change (gymnosperm to angiosperm) can only amplify the CIEs (Schouten et al., 2007; Smith et al., 2007). The net result may be an offset of the CIEs from actual CIEs, possibly by 1–2‰ (Bowen et al., 2004; Uchikawa and Zeebe, 2010). Since, plant community change (i.e., gymnosperm to angiosperm) could not occur near the equator (Jaramillo, 2002; Jaramillo et al., 2006; Jaramillo et al., 2010), $\delta^{13}C$ of bulk organic matter from the equatorial region could only be influenced by hydrologic cycle over and above the actual CIEs, and can shed light on the change in precipitation regime in the tropics during the CIEs. Here we report the PETM and all early Eocene CIEs from bulk organic matter, hitherto unknown from tropical terrestrial records (Fig. 1a). This first PETM report from an Indian section also exhibits comparatively higher magnitude of the CIEs (PETM: ~5.1‰, H1: 2.6‰, H2: ~2‰, I1: 2.1‰, and I2: 2‰) and demands an increased precipitation regime in the equator during the early Eocene predicted by general circulation models.

Further, we make an attempt to constrain absolute age of the PETM and EEHs by Ar–Ar thermochronology of authigenic glauconites preserved in these sections. This is important because the absolute age for the onset of PETM is not very well constrained due to the absence of a datable material (e.g. ash layer) within the PETM body itself. Using radiometric dates of marine ash layers +19 and −17 within magnetochron C24r and orbital tuning of marine sediments the age of the PETM CIE onset has recently been estimated as 56.011–56.293 Ma (Westerhold et al., 2009). Jaramillo et al. (2010) dated the PETM (56.09 ± 0.03) from a terrestrial section by U–Pb dating of zircon separated from a tuff lying in the upper part of the PETM body. The glauconites dated in the present study occur exactly within the bodies of the PETM and EEHs and hence have added significance to the chronology of these hyperthermals.

2. Materials and methods

Sediment samples of the Cambay shale Formation were collected from both Vastan (21° 26.152′N and 73° 06.968′E; Fig. 1b) and Valia (21° 35.837′N and 73° 12.027′E; Fig. 1b). At Vastan, samples were taken from 60 m thick exposed section of the Vastan mine face as well as ~100 m drill core raised by the Gujarat Industrial Power Corporation Limited (GIPCL). Later composite litholog was prepared using the ~10 m thick upper coal seam (Fig. 2) and Nummulites bearing zone identified in both mine face and also in the core. Another ~320 m drill core penetrating up to the late Cretaceous Deccan Trap basalt was raised from Valia, at ~20 km NE of the Vastan. The sampling resolution at Valia is higher (at ~50 cm interval throughout the core) than that of Vastan (50 cm to 1 m). Nannofossils were separated from the Vastan sediments by standard random settling technique, smear-slides prepared and studied with a polarizing microscope. Selected slides were gold sputtered and studied under a Scanning Electron Microscope (SEM) at Birbal Sahni Institute of Palaeobotany, Lucknow. Quantitative estimations were made by counting index species per unit area. For pollen analysis, sediments were treated with a 10% KOH solution to dissolve humic acid and liberate palynomorphs. Material was sieved through 200 μm mesh, filtrate centrifuged, washed and processed by the conventional technique of acetolysis. Palynomorphs were mounted for microscopic study with 50% glycerin and pollen grains were counted in each sample for quantitative estimation.

For $\delta^{13}C$ analysis of bulk organic matter ~1–50 mg de-carbonated sample was combusted in a Flash Elemental Analyzer. The evolved CO_2, purified through a moisture trap, was measured for its isotopic

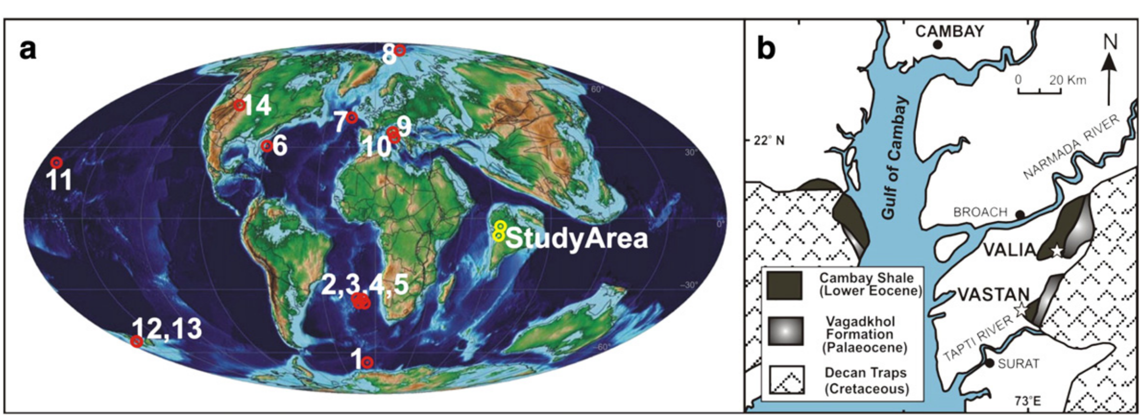

Fig. 1. (a) Paleogeographic locations of the study area and other PETM sections where all Eocene hyperthermals have been documented (Supplementary Table 5); note paucity of tropical hyperthermal sites. 1 = ODP 690; 2 = ODP 1262; 3 = ODP 1263; 4 = ODP 1265; 5 = ODP 1267; 6 = ODP 1051; 7 = DSDP 550; 8 = Lomonosov Ridge; 9 = Possagno section, Italy; 10 = Contessa section; 11 = DSDP 577; 12 = Mead Stream, New Zealand; 13 = Dee Stream, New Zealand; 14 = Bighorn Basin, Wyoming, U.S.A. (b) Detailed geological map of Vastan and Valia areas.