Late Paleocene–early Eocene carbon isotope stratigraphy from a near-terrestrial tropical section and antiquity of Indian mammals

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Late Paleocene to early Eocene (~56 to 51 Ma) interval is characterized by five distinct transient warming (hyperthermal) events (Paleocene–Eocene thermal maximum (PETM), H1/ETM2/ELMO, H2, I1 and I2) in a super greenhouse globe associated with negative carbon isotope excursions (CIEs). Although well-documented marine records exist at different latitudes, terrestrial PETM sections are rare. In particular, almost no terrestrial records of either the PETM or early Eocene hyperthermals (EEHs) are yet available from the tropics. Further, evolution of modern order of mammals near the PETM has been recorded in many northern continents; however, the response of mammals in the tropics to these warming events is unknown. A tropical terrestrial record of these hyperthermal/CIE events, encompassing the earliest modern order mammal bearing horizon from India, can therefore be vital in understanding climatic and biotic evolution during the earliest Cenozoic time. Here, for the first time, we report high resolution carbon isotope ($\delta^{13}\text{C}$) stratigraphy, nannofossil, and Sr isotope ratio of marine fossil carbonate from the Cambay Shale Formation of Western India. The record shows complete preservation of all the above CIE events, including the PETM, hitherto unknown from the equatorial terrestrial records. $\delta^{13}\text{C}$ chemostratigraphy further suggests that at least the present early Eocene mammal-bearing horizon, recently discovered at Vastan, does not support the ‘out of India’ hypothesis of earliest appearance of modern mammals and subsequent dispersal to the Holarctic continents.

1. Introduction

The transition from late Paleocene to early Eocene (~56 to 51 Ma) witnessed a series of short-lived hyperthermal events (Paleocene–Eocene thermal maximum (PETM), H1/ETM2/ELMO, H2, I1, and I2), superimposed on the long-term global warming trend (Cramer *et al.* 2003; Nicolo *et al.* 2007; Zachos *et al.* 2010). Each hyperthermal

event, lasting between 50 and 200 Kyr, is marked by characteristic negative carbon isotope excursions (CIEs), signifying rapid addition of ^{13}C -depleted carbon to the exogenic carbon cycle (Lourens *et al.* 2005; Zachos *et al.* 2010). Among the CIEs, only the PETM (~55.5 Ma) is globally well-recognized, while the other early Eocene hyperthermals (EEHs) have been recorded mostly from few high-latitude deep ocean sites (figure 1a).

Keywords. Tropical terrestrial Paleocene–Eocene thermal maximum (PETM); early Eocene hyperthermals; carbon isotope excursion; modern order mammal.

Figure 1. (a) Paleogeographic locations of Vastan and other PETM sections where all Eocene hyperthermals have been documented; 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. (b) Detailed geological map of Vastan area.

Equatorial or shallow marine records of these EEHs are rare, viz., only at DSDP/ODP sites 577, 1215, and off-New Zealand coast. Almost completely absent are the tropical terrestrial records of either the PETM or EEHs (Nicolo *et al.* 2007; Leon-Rodriguez and Dickens 2010). While the PETM has been reported from terrestrial sections of Colombia and Venezuela (Jaramillo *et al.* 2010), only one record of terrestrial ETM2 has been reported from Vastan Lignite mine, India (Clementz *et al.* 2011).

Apart from its importance in understanding the climate dynamics in a greenhouse globe, such climate extremes presumably played an important role in the biotic evolution also as several modern orders of mammals (artiodactyls, perissodactyls, and primates or artiodactyls, perissodactyls, and primates (APP) taxa) first appeared nearly concurrently in the Holarctic continents (North America, Europe and Asia) during this interval (Gingerich 2006; Smith *et al.* 2006). However, the first appearance datum of the APP taxa in North America (Polecat Bench, Bighorn basin) and China (Hengyang Basin) show marked chronological discordance when compared with the high resolution carbon isotope stratigraphy. While, the appearance of APP taxa at North America occurred within the PETM CIE body (Smith *et al.* 2006), in China they appeared at the base of the PETM CIE (Bowen *et al.* 2002). Recent discovery of exciting assemblages of terrestrial mammalian fauna, viz., euprimates (*adapoids*, *omomyids*, etc.), Laurasian artiodactyl *Diacodexis*, Perissodactyla, rodent *Melomys*, primitive lagomorph, and many other forms from the Vastan mine led to the suggestion that the earliest mammals might have migrated from southern Asia (e.g., China) to Indian subcontinent near the PETM (Rose *et al.*

2009). The mammal assemblage in the Ghazi formation, Pakistan is also suggestive of modern mammalian dispersal during initial India–Asia collision (Clyde *et al.* 2003). An alternative speculation is that many of these early modern mammals might have originated in island-India during its northward drift towards Eurasia and later migrated to northern continents after the India–Eurasia collision (Bajpai *et al.* 2008; Clementz *et al.* 2011). This has been termed as ‘Out of India’ hypothesis in many recent literature (see Rust *et al.* 2010 for detail). Fundamental to this speculative hypothesis is the identification of the PETM interval and the exact chronological assignment of the mammal layers relative to the PETM CIE in the Vastan mine section. Here, for the first time, we report near-terrestrial equatorial PETM section with all subsequent EEHs within the Cambay Shale Formation at Vastan lignite mine, southern Cambay basin, western India. Our study shows that the mammal layer at Vastan is substantially younger than the PETM, thus casting doubt about the ‘out of India’ hypothesis.

2. Materials and methods

Sediment samples of Cambay Shale Formation were collected from both 60 m thick exposed section of the Vastan mine face (21°26.152'N and 73°06.968'E; figure 1b) as well as ~100 m drill core raised by the Gujarat Industrial Power Corporation Limited (GIPCL) at Vastan. The composite litholog was prepared using the ~10 m thick upper coal seam (figure 2) and upper fossiliferous grey shale layer identified in both mine face and core.

Figure 2. Field photograph of the Vastan mine section and representative composite litholog showing the position of mammal layer, *Nummulites burdigalensis* (Nb) zone and ETM2/H1 hyperthermal. The column to the left of the litholog shows the actual sediment colours.

For $\delta^{13}\text{C}$ analysis of bulk organic matter ~ 1 –50 mg decarbonated sample was combusted in a flash elemental analyser. The evolved CO_2 , purified through a moisture trap, was measured for its isotopic compositions in a Delta Plus XP continuous flow mass spectrometer (analytical precision $\pm 0.1\text{‰}$) at National Stable Isotope Facility, Indian Institute of Technology, Kharagpur. For strontium (Sr) isotope, fossil shell samples were ultrasonically cleaned, dried, leached in ultrapure 1 N HCl and residue removed. Sr was separated from the leachate by conventional cation exchange column chromatography and loaded onto a tantalum filament. $^{87}\text{Sr}/^{86}\text{Sr}$ was measured in a Thermo Fischer Triton thermal ionization mass spectrometer at the KDM Institute of Petroleum Exploration, Dehradun. The measured ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. All sample ratios were adjusted to measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of NIST 987 standard. Nannofossils were separated by standard random settling technique, smear-slides prepared and studied with a polarizing microscope. Selected slides were gold sputtered and studied under scanning electron microscope (SEM) at Birbal Sahni Institute of Palaeobotany, Lucknow.

3. Results and discussion

3.1 Depositional environment of the Vastan sequence

Formed by intracratonic rifting, the Cambay basin hosts ~ 8 km of fluvio-lacustrine sediments (with

minor marine intervals) as a result of episodic subsidence from late Cretaceous to Miocene period (Biswas 1987). The shale–lignite sequence at Vastan, belonging to Cambay Shale Formation, was directly deposited over the Deccan Trap basement (Punekar and Saraswati 2010). The sequence comprises alternate lignite and grey shale encasing thick (metre scale) wedge-shaped coquina-like marine shell beds and centimetre to decimetre scale silt/fine sand lenses (figure 2). Dominant fine-grained sediments, anoxic to dysoxic facies (e.g., coal/black-/grey-shale), general absence of tide or wave features, profuse bioturbations in grey shales and lenticular silt/sand/shell beds indicate deposition in a possible lagoonal environment (Holz 2003). In particular, the lagoonal beds at Vastan contain two prominent marine incursion horizons, the lower one yielding rich marine bivalve assemblage at ~ 200 m depth and the upper one at ~ 170 m depth yielding both marine bivalves as well as larger benthic foraminifers (e.g., *Nummulites* reported by Punekar and Saraswati 2010). These intervals possibly represent discrete high sea stands with more open ocean connectivity in this lagoon. It is, however, important to note that although marine beds occur at certain levels, thinner lignite layers are present throughout the sequence signifying a dominant near-terrestrial environment.

3.2 Chronology

In Vastan thermophilic calcareous nannofossil, assemblage first appears near the lower marine

bivalve rich horizon at a depth of ~ 215 m and extends up to ~ 190 m and represented by *Discoaster araneus* (nannoplankton zone (NP) 9b to NP10a), *Rhomboaster cuspis* (NP9b to NP10a; Aubry 1999), *Tribrachiatus bramlettei* (NP10 to NP11; Martini 1971), and *Fasciculithus tympaniformis* (end of NP4 to NP9b; figure 3). Base of *T. bramlettei*, *D. araneus* and *R. cuspis* typically coincides with the PETM, while *F. tympaniformis* terminates at the PETM. This unique association of *T. bramlettei*, *D. araneus*, *R. cuspis* and *F. tympaniformis* is globally assigned as the PETM (Raffi et al. 2005). Based on this evidence, we consider the depth interval between 215 and 190 m below the Vastan mine section to be equivalent to the PETM. Larger benthic foraminifera *Nummulites burdigalensis burdigalensis* and *N. burdigalensis kuepperi* occur in the upper marine horizon (160–170 m, Punekar and Saraswati 2010) corresponding to early shallow benthic zone (SBZ) 10. Based on the latest magnetostratigraphy of Gradstein et al. (2004) and re-calibration of the SBZ-10 by Mochales et al. (2012), the time span of SBZ-10 has recently been revised from 51.5 to 53.5 Ma (see later discussion). To ascertain the chronology of the sequence, we also carried out $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of marine bivalves from both lower and upper

fossiliferous intervals of Vastan, which have excellently preserved pristine aragonitic shells (figure 4 inset). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of these shells varies from 0.707708 ± 4 to 0.707766 ± 4 . These ratios are similar to those reported by Clementz et al. (2011). Using the strontium isotope stratigraphic calibration of McArthur and Howarth (2004), the numerical best fit ages of these bivalves (red dots with vertical bar, figure 4) range between ~ 56.5 and 52 Ma. Considering the new and published $^{87}\text{Sr}/^{86}\text{Sr}$ data along with the biostratigraphic ages, it can be inferred that the age of the Vastan sequence ranges from ~ 56.5 to at least 52 Ma. The above chronology of Vastan is further supported by their corresponding $\delta^{13}\text{C}$ chemostratigraphy (see later discussion on carbon isotope stratigraphy).

3.3 Diagenesis and sources of organic matter

Two major uncertainties associated with the use of bulk organic matter $\delta^{13}\text{C}$ stratigraphy are (i) post-depositional diagenetic modification and (ii) facies or lithology-dependent mixing of diverse sources of organic matter. Almost all the marine bivalves at Vastan have exceptionally well-preserved aragonitic shells (figure 4 inset). As discussed above,

Figure 3. Typical nannofossil biostratigraphic ranges across the PETM and light microscopic (1–5) and SEM (6–7) photographs of their occurrences in Vastan at ~ 200 m depth. (1) *Tribrachiatus bramlettei* (Proto Decima et al. 1975), (2) *Fasciculithus tympaniformis* (Hay and Mohler 1967), (3–4) *Rhomboaster cuspis* (Bramlette and Sullivan 1961), (5) *Discoaster araneus* (Bukry and Percival 1971), (6–7) *Rhomboaster cuspis*.

Figure 4. Chronology of Vastan sediments based on strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of marine bivalves (red dots). Also plotted previously published ratios of Vastan carbonates by Clementz *et al.* (green dots, 2011) and data used by McArthur and Howarth (2004; gray dots) for age calibration. Vertical bars represent analytical errors ($\pm 2\sigma$). Inset showing photograph of preserved aragonitic bivalve shells from which Sr ratios were measured.

these carbonates also preserved pristine Paleocene–early Eocene marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Biomarker isotopes of Vastan resins even identified the plant community at generic level (Dutta *et al.* 2011) suggesting minimal diagenesis. Thermochemolysis of the lignites suggest preservation of lignin compounds in these rocks indicating their derivation from terrestrial plants (Dutta *et al.* 2012). Apart from diagenesis, another factor that might potentially complicate the interpretation of $\delta^{13}\text{C}$ stratigraphy is the facies-dependent mixing of diverse source of organic matter. Different kinds of vegetation might thrive on different sedimentary facies namely, proximal or distal part of a depositional ecosystem (e.g., river floodplain, bar or lagoon bank). No specific bias towards specific lithofacies on the frequency distribution of $\delta^{13}\text{C}$ was observed indicating that isotopic compositions are facies-independent and can be used for palaeoclimatic inferences.

3.4 $\delta^{13}\text{C}$ stratigraphy

Figure 5 shows the bulk organic matter $\delta^{13}\text{C}$ stratigraphy at Vastan. Five distinct negative CIEs are observed upward from the base of the section. The first major CIE occurs between 231.85 and

194 m depth with magnitude ($\Delta\delta^{13}\text{C}$, base to peak difference in $\delta^{13}\text{C}$ of the excursion) of 5.2‰. The other four CIEs occur at 152.5 m ($\Delta\delta^{13}\text{C} = 2.2‰$), 140.7 m ($\Delta\delta^{13}\text{C} = 2.2‰$), 134.5 m ($\Delta\delta^{13}\text{C} = 1.6‰$), and 117 m ($\Delta\delta^{13}\text{C} = 2.3‰$) depths. Using the Sr isotope ratios and partial $\delta^{13}\text{C}$ profile, the peak from a level close to 152.5 m in the Vastan mine section has already been identified by Clementz *et al.* (2011) as ETM2 (green CIE in figure 6). Based on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (as discussed earlier) and association of *Tribrachiatulus bramlettei*, *Discoaster araneus*, *Rhombaster cuspis* and *Fasciculithus tympaniformis*; we interpret the lowermost and largest plateau like CIE at Vastan ($\Delta\delta^{13}\text{C} = 5.2‰$) as the PETM. Up in the section, the second excursion of 2.2‰ is found within the thickest lignite seam at ~152.5 m depth. From the presence of *Nummulites burdigalensis burdigalensis* and *N. burdigalensis kuepperi* just below this seam (figures 5, 6) Punekar and Saraswati (2010) earlier assigned it to be equivalent to early SBZ-10 (following Serra-Kiel *et al.* 1998). The earlier age of SBZ-10 (~52.7–~50.7 Ma) was calibrated against an old-time scale of Berggren *et al.* (1995). However, using the latest available Geomagnetic Polarity Time Scale (GTPS; Gradstein *et al.* 2004), Mochales *et al.* (2012) showed that the base of the SBZ 10 is substantially older (~53.5 Ma) than previously thought and lies within the magnetic Chron C24n.2n. Based on this, the CIE at ~152.5 m can be considered as ETM2. However, unlike the PETM, it has not been possible to assign an absolute date for the ETM2. The date of the PETM, i.e., 55.53 ± 0.05 Ma is now well-established using both the astronomical calibration and absolute radiogenic isotope date of the Eocene ash-17 layer from the ocean drilling program (ODP) section 1262 (see Westerhold *et al.* 2012). On the other hand, no datable horizon has so far been found near ETM2 and its age assignment has been done based only on the combination of magneto-stratigraphy and orbital chronology. This suggests that the time gap between the PETM and the ETM2 is either 2.25 myr (spans ~21 eccentricity cycle, Lourens *et al.* 2005) or 1.83 myr (spans ~19 eccentricity cycle, Westerhold *et al.* 2007). Considering 55.5 Ma absolute age of the PETM, the age of the ETM2 could be either ~53.25 or 53.67 Ma. The ranges of both SBZ-10 (green bar) and ETM2 (blue bar) are shown in figure 5, which shows an overlapping range. Based on these observations, we conclude that the CIE at ~152.5 m depth as the H1/ETM2/ELMO (Lourens *et al.* 2005; Zachos *et al.* 2010; Clementz *et al.* 2011). The shape, amplitude and approximate timing suggest that the three CIEs, overlying the ETM2, are possibly the H2, I1 and I2 (figures 5, 6; Zachos *et al.* 2010).

Figure 5. Lithologs along with bulk organic matter $\delta^{13}\text{C}$ at Vastan. The $\delta^{13}\text{C}$ stratigraphy is compared and correlated with carbonate $\delta^{13}\text{C}$ stratigraphy of ODP 1051 of Southern Ocean best recording the EEHs. Amplified magnitudes of the Vastan section compared to the marine records of both PETM and EEHs are clearly discernible. ETM2 (blue bar) and SBZ 10 (green bar) age ranges show an overlap of about ~ 0.25 Ma (for details see text).

The carbonate $\delta^{13}\text{C}$ profile at ODP site 1051 in the southern ocean, that records best the EEHs, is plotted with the $\delta^{13}\text{C}$ profile of Vastan in figure 5. The dotted lines in figure 5 denote the correlation of the PETM and EEHs with the marine records. The CIEs in deep sea carbonates are severely attenuated by dissolution effect due to ocean acidification (Nicolo *et al.* 2007; Smith *et al.* 2007), thus questioning the magnitude of these events and their global nature. The present study, for the first time, documents all five hyperthermal/CIE events, including the PETM, in a near-terrestrial equatorial sequence with $\Delta\delta^{13}\text{C}$ of the CIEs larger than or equal to those recorded elsewhere and suggest these to be global in nature. Figure 6 shows the correlation of the Vastan $\delta^{13}\text{C}$ profile with two published terrestrial sections from Claret, Spain and Honeycombs, North America (Domingo *et al.* 2009). The PETM interval at all these three terrestrial sections are similar and much expanded (~ 30 – 40 m) compared to the marine PETMs. An additional CIE is observed immediately after the PETM at ~ 190 m in Vastan. Such an excursion

has also been observed in Claret and Honeycombs sections, although its significance is not fully understood. Identification of the PETM and other EEHs at this location provides evidence of the early Cenozoic carbon cycle perturbations even in tropical terrestrial realm. The large magnitudes of the CIE of either the PETM ($\sim 5.2\text{‰}$) or other EEHs at Vastan suggest that (1) the perturbation was recurring in nature and (2) cannot possibly be explained only by the dissociation of marine gas hydrates, since it would require an unrealistic instability of hydrate reservoir over a long period of ~ 3 – 4 Myr (i.e., 55–52 Ma). Recent studies in fact suggest an alternative source of methane from terrestrial swamps and peat lands triggered during this ancient super-greenhouse condition (Pancost *et al.* 2007; DeConto *et al.* 2012). Estimation based on the global distribution of coal-bearing facies suggest that during the late Paleocene–early Eocene aerial extension of wet land/peat land was ~ 3 times higher than today (Sloan *et al.* 1992; Beerling *et al.* 2011). Strong evidences exist about enhanced methane emission from wet land due to

Figure 6. High resolution record of bulk organic matter $\delta^{13}\text{C}$ of Vastan compared with continental Claret (Spain; in red) and Honeycombs (North America; in blue) section. Previously reported ETM2/H1 CIE at Vastan is also shown (in green). Note that the mammal horizon at Vastan is much younger than either the PETM or Holarctic taxa of China (discussion in text).

ongoing global warming (Turetsky *et al.* 2008). If so, methane from wet land could easily inject depleted carbon into the ocean–atmosphere system causing hyperthermal CIEs during the late Paleocene and early Eocene. Indeed, recently observed depletion in $\delta^{13}\text{C}$ of hopanoids (a biomarker of methanotrophic bacteria) across a lignitic PETM sequence (Pancost *et al.* 2007) supports significant role of methanogenic carbon emission from wet land and peat land that was much more extensive in a warm early Eocene globe.

3.5 Antiquity of modern Indian mammals

Detection of PETM at Vastan has an added implication. Our data, for the first time, reports the PETM interval at Vastan and clearly shows that the mammal layers are significantly younger than the PETM interval (figure 6). Considering the age of termination of the PETM (~55.3 Ma) and ETM2 (~53.7 or ~53.25 Ma; Lourens *et al.* 2005; Zachos *et al.* 2010) and the intervening

sediment thickness (without decompacting), the age of the mammal layer is close to a million years younger than the PETM, thus raising doubts about the ‘out of India’ hypothesis. Although molecular clock estimation suggested origin of many modern vertebrate lineages and mammalian taxa in an isolated drifting Indian continent (Krause and Maas 1990; Bossuyt and Milinkovitch 2001) which later dispersed and colonized in rest of the world, the revival of ‘out of India’ hypothesis took place when oldest (~55 Ma) Anthroidea (*Anthrasimias gujaratensis*) was claimed to have been discovered in Vastan (Bajpai *et al.* 2008; Clementz *et al.* 2011). Assignment of this *Anthrasimias*, on the basis of differentiating small cusps in isolated teeth, has been questioned and considered to be unreliable phylogenetic indicator (Rose *et al.* 2009). An exhaustive analysis of Vastan fauna suggests that none of the primates namely, omomyids, adapoids, Asiadapines, etc. either originated in India or are more primitive than their counterparts found elsewhere (Rose *et al.* 2009). The only unequivocal evidence of oldest

Asian mammalian fauna comes from Hengyang Basin, Hunan province of China, where diverse APP taxa have indeed been found from horizons near the PETM carbon isotope excursion (Bowen *et al.* 2002; figure 6). Our data suggest that the Vastan mammals appeared at least a million years later than those of China (figure 6) and questions the antiquity of Indian mammals. Thus, pending the discovery of still older (at or pre-PETM) fossil records, the present work seriously raises questions about the antiquity of Vastan mammals. As suggested by Rose *et al.* (2009), most likely these fauna migrated into India, near the PETM, after the establishment of land-bridge due to India–Eurasia collision.

4. Summary

High resolution carbon isotope ($\delta^{13}\text{C}$) stratigraphy, nannofossil, and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of fossil carbonate shells of lagoonal lignite beds of Vastan area from the Cambay Shale, India have been studied. Data show complete preservation of all the early Eocene CIE events (viz., H1/ETM2/ELMO, H2, I1 and I2) including the PETM, hitherto unknown from the tropical terrestrial records. The $\delta^{13}\text{C}$ chemostratigraphy further suggests that the present early Eocene Indian mammalian fossil bearing horizon, recently discovered at Vastan, is at least ~ 1 Myr younger than the PETM. Unless older (at or pre-PETM) fossil mammals are found, the present dataset does not support the ‘out of India’ hypothesis of earliest appearance of modern mammals and their subsequent dispersal to the Holarctic continents.

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