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Cool equatorial terrestrial temperatures and the South Asian monsoon in the Early Eocene: Evidence from the Gurha Mine, Rajasthan, India

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A B S T R A C T

Early Eocene (~55–52 Ma) laminated lacustrine sediments overlying lignites in the Gurha Mine (27.87398°N, 72.86709°E), Rajasthan, India, yield a diversity of fossil leaves, flowers, fruits, seeds and insects. CLAMP (multivariate foliar physiognomic) analysis of two horizons separated by an estimated several tens of thousands of years of deposition indicates cool equatorial (~10°N) temperatures and a pronounced monsoon signature. A lower assemblage consisting of 54 leaf morphotypes and an upper assemblage of 57 leaf forms yielded mean annual temperatures (MAT) of 24.7 and 23.9 °C, respectively. The uncertainty (±2.82 °C) means these temperature regimes are identical despite few similarities in the morphotypes between the two assemblages.The mean annual range of temperature (MART) was approximately 9.7 °C for both assemblages. When corrected for evapotranspirational cooling these temperature regimes are similar to those experienced today at 10°N on the west coast of India and surprisingly cool for the tropics at a time of extreme global warmth. Growth was year round. The tropical to paratropical fossil floras also suggest a moist regime (80% annual relative humidity) and high mean annual precipitation of ~1800 mm for both assemblages but with a pronounced wet/dry seasonality indicative of a pronounced monsoonal regime. The lower assemblage has a stronger monsoon index (11.8) than the upper assemblage (8.8). The two assemblages seem to have been deposited less than 100 ka apart. This suggests that not only a pronounced South Asian monsoon existed when India and Asia first made contact, but also a variation in monsoon strength existed that cannot be ascribed to tectonic drivers.

1. Introduction

1.1. Early Eocene temperatures

The early Eocene witnessed the warmest temperatures of the Cenozoic, initially in the form of a short lived (~200 ka) thermal spike of 5–8 °C recorded in global deep marine environments (Kennett and Stott, 1991; Thomas et al., 1996; Zachos et al., 2001; Thomas et al., 2002; Zachos et al., 2003; Tripati and Elderfield, 2005; Sluijs et al., 2006), often referred to as the Paleocene–Eocene Thermal Maximum or PETM, then by a more persistent early Eocene 'climatic optimum' lasting several million years at around 52 Ma (Zachos et al., 2001), followed by a gradual cooling. A similar PETM temperature spike has been recorded on land as evidenced by leaf margin analysis and oxygen isotope analysis of soil carbonates, fish scales and mammalian tooth enamel (Bowen et al., 2001; Koch et al., 2003; Fricke and Wing, 2004). This event was associated with a negative Carbon Isotope Excursion (CIE) and a possible warming mechanism was the release of thousands of petagrams of carbon into the atmosphere over an interval of 20 ka. Silicate weathering and terrestrial and marine carbon sequestration returned atmospheric carbon levels to those that existed immediately prior to the PETM over a period of 200 ka. Warming drove poleward migration of both marine and terrestrial biota from the tropics and was associated with rapid evolutionary change, but there were few extinctions except among benthic foraminifera (McInerney and Wing, 2011, and references therein). Deep marine proxies also record the early Eocene 'climatic optimum' beginning at around 52 Ma (Zachos et al., 2001) but deep marine temperatures are not necessarily an indication of air temperatures over land and, because ocean response times are much longer than those of the atmosphere, inevitably fail to capture short duration (<2 ka) thermal oscillations.

That the high latitudes were warm throughout the Eocene is beyond doubt as evidenced by highly productive ecosystems populated by cold intolerant organisms (Eberle and Greenwood, 2012). More controversial has been the characterisation of low latitude climates, particularly when isotopic systems are so prone to diagenetic effects (Norris and Wilson, 1998; Schrag, 1999; Wilson et al., 2002). Diagenetic alteration initially resulted in surprisingly cool equatorial temperature estimates for the Cretaceous and Paleogene (Shackleton and Boersma, 1981; Bralower et al., 1995; D'Hondt and Arthur, 1996; Dutton et al., 2005), but analysis of unaltered material subsequently revised these

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temperatures upwards (Pearson et al., 2001, 2007). Maximum sea surface temperatures (SSTs) were estimated to have been mostly >30 °C, and some as high as 34 °C, implying considerably warmer terrestrial daily peak air temperatures. Today such temperatures compromise primary productivity in land plants by enhancing photorespiration and destroying lipid membranes (Muraki et al., 2000; Sharkey, 2000). Organic geochemical proxies, while less prone to diagenetic effects, yield even higher tropical SSTs of between 35 and 40 °C during the warmest early Eocene interval, and if these temperatures reflect past reality tropical vegetation should have suffered mass mortality (Huber, 2008). There is some evidence for this, but only during extremely warm but short-lived (~200 ka) episodes such as that at the PETM (Harrington and Jaramillo, 2007), and even then the effect appears surprisingly muted.

A general characteristic of such ancient 'hothouse' climates is that proxies indicate a markedly lower equator-to-pole temperature gradient than during cooler periods (e.g. Greenwood and Wing, 1995; Spicer and Herman, 2010). However, the failure of climate models to reproduce such shallow gradients persists despite decades of attempts to warm the poles without overheating the equator (Valdes, 2000). When models are constrained to generate polar temperatures consistent with those revealed by geological proxies invariably the modelled tropics are too warm to sustain primary productivity. In the absence of reliable 'hothouse' climate models there is a clear need to characterise better low latitude air temperatures during such thermal extremes, not the least because present models are likely to underestimate the effects of future warming (Spicer et al., 2008 in press).

Not all marine proxies indicate extreme warmth in the early Eocene. Studies of early Eocene (54–52 Ma) bivalves from the Gulf Coastal Plain of the USA (palaeolatitude ~30°N, Müller et al., 2011) indicate a shallow marine mean annual temperature (MAT) of ~27 °C (Keating-Bitonti et al., 2011). This study combined stable oxygen isotope, clumped isotopes, and strontium isotope analyses of shell carbonate with tetraether lipid proxies (TEX_{86}, BIT [branched and isoprenoidtetraether], MBT/CBT [methylation of branched tetraethers/cyclization of branched tetraethers]) from organic matter in sediment enclosed by articulated shells and so correction for salinity effects that influence stable isotope-derived temperature estimates was possible. Keating-Bitonti et al. (2011) suggest that the Eocene low latitudes were perhaps not as uniformly warm as previously thought. In Asia Yao et al. (2009) using the Co-existence Approach of Mosbrugger and Utescher (1997) report that the MAT of the supposedly early Eocene Changchang Formation palynoflora of southern China (Hainan Island) was no more than 19.2 °C. It should be noted, however, that this perceived cool temperature could in part have been caused by the inclusion of pollen derived from plants growing at elevation. The palaeolatitude of the Changchang deposit was ~22°N (http://www.odsn.de; Scotese, 2001) during the early Eocene.

To contribute to a better understanding of equatorial atmospheric conditions during the early Eocene here we examine the climate signal contained within two low palaeolatitude (<10°N) plant fossil assemblages from Rajasthan, northwestern India. We focus on leaf fossils that, unlike pollen, are likely to represent vegetation growing near to the site of deposition.

2. Materials and methods

2.1. Geology

The Gurha Lignite Mine (East) is an opencast site located in western Rajasthan (27.87398°N, 72.86709°E) 47 km WSW from the town of Bikaner (Fig. 1). An initial visit to the mine was made in January 2012 by Drs Mehrotra and Shukla who made the first collection of fossil material. A return visit was made in late February–early March 2012 to document the then exposed section and to make further palaeontological collections.

2.1.1. Age of the Gurha fossiliferous units

Lapilli tuffs occurring below the lignite exposed in the bottom of the mine in 2012 proved to be altered to clay and were not dateable. Pollen assemblages from the Gurha mine are still under investigation and will be described and illustrated in detail elsewhere. Nevertheless the occurrence of the following taxa in the Gurha palynoassemblages indicates an early Eocene age: *Dandotiaspora telonata*, *Palmidites plicatus*, *Palmaepollenites eocenicus*, *Matanomadhiasulcites matanomadhensis*, *Retitribrevicolporites matanomadhensis*, *Tricolpites reticulatus*, *Triorites bellus*, *Lakiapollis ovatus*, *Clavaperiporites clavatus*, *Lanagiopollis rugularis*, *Tricolporopollis rubra*, *Rhoipites kutchensis*, *Retistephanocolporites* sp., *Sastripollenites trilobatus*, *Katariacolporites plicatus*, *Clavaperiporites jacobei*, *Crototricolpites densus*, *Triangulorites bellus*, *Dermatobrevicolporites exaltus* and *Kielmeyerapollenites eocenicus*. The last seven of those listed are particularly characteristic of the early Eocene as they have been recorded from the early Eocene Naredi Formation of the Kutch Basin (Kar and Saxena, 1981; Kar, 1985) and Cambay Shale Formation of the Cambay Basin (Kumar, 1996; Rao et al., 2013); the latter includes Rajpardi and Vastan lignite deposits located about 700 km to the south of the Gurha Mine.

Previous work also suggests that the carbonaceous and 'coal' deposits in this vicinity are coeval with the early Eocene Vastan lignites of Gujarat (Sahni et al., 2004), which interfinger with well-dated marine units. The Vastan lignite successions are highly fossiliferous having yielded pollen (Samant and Tapaswi, 2000, 2001), plant remains of various kinds (Sahni et al., 2006), dinoflagellates (Garg et al., 2008), marine ostracodes (Bhandari et al., 2005), marine fish (Samant and Bajpai, 2001; Rana et al., 2004; Nolf et al., 2006), and mammals (Sahni et al., 2004; Rose et al, 2006) including bats (Rana et al, 2005). To-date the Gurha Mine has yielded no unequivocal marine units. The abundant leaves, flowers, wood, pollen and insects appear instead to have been deposited in a poorly oxygenated lacustrine environment represented by laminated clays and sands belonging to the Palana Formation.

The Vastan lignites (Gujarat) were deposited in a low energy coastal marsh-bay complex with distinct depositional facies representing open bay, restricted bay, creek and channel environments. In a comprehensive sequence stratigraphic and palynofacies examination of the Vastan Lignite Mine succession Prasad et al. (2013) suggest that the maximum flooding surface, represented by evidence of greatest marine incursion, coincides with a negative ~4‰ $\partial^{13}C$ excursion at 53.7 Ma, but that the Vastan succession overall can only be constrained to be between ~55 and 52 Ma. Given the similarities in floral composition, depositional setting and the overall regional stratigraphy we regard the Gurha sediments to be of approximately the same age.

2.1.2. Palaeoposition of the Gurha flora

Fig. 1 illustrates the palaeoposition of the Gurha Mine site in the early Eocene (~50 Ma) based on data presented in Molnar and Stock (2009). This shows that in the early Eocene the palaeolatitude of the Gurha Mine was approximately 9°N. The extent of greater India to the north of the Gurha depositional site is unclear, but the depositional site was near the western coastline as evidenced by mapped marine deposits associated with coeval lignites nearby in Gujarat (Sahni et al., 2006).

2.2. CLAMP methodology

Our palaeoclimatic analysis of the Gurha leaf flora was performed using the multivariate foliar physiognomic proxy known as Climate Leaf Analysis Multivariate Program (CLAMP) (Wolfe, 1993; Kovach and Spicer, 1995; Yang et al., 2011). Underpinning the technique is the use of Canonical Correspondence Analysis (CCA) (terBraak, 1986) to position modern and fossil leaf physiognomy data relative to one another in multidimensional physiognomic space calibrated using high-resolution gridded climate data. The climate calibration was derived from the global gridded data of New et al. (2002) following the approach of Spicer et al. (2009) as generated by the BRIDGE website.