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Early Eocene biotic assemblage from the sedimentary deposits of the Tarkeshwar Lignite Mine, Gujarat and its palaeoenvironmental implications

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ABSTRACT

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The Palaeogene biota and the palaeoenvironmental history from the low latitudes are remarkably well–preserved in the open–cast lignite deposits from western India. Lignite sequences of the Cambay Shale Formation (Gujarat) have been a major source to understand the concept of early evolution of fossils including flora, arthropods, vertebrates fauna, and several aquatic forms during the Early Eocene. The study deals with an extensive record of amber inclusions and extracted pollen, vertebrate fragments, dinoflagellate cysts and carbon isotopes from the lignite and associated sediments from the Tarkeshwar Lignite Mine to add insights into the palaeoenvironment and depositional conditions of the Cambay Basin during the Early Eocene Period. The current study demonstrates that throughout the Late Palaeocene – Early Eocene Epoch, the palaeoenvironment changed from low land, marshy (lower portion), to shallow marine environment, presumably due to hyperthermal event PETM (middle part). Age diagnostic taxa, viz. *Auxiodinium longispinosum*, *Apectodinium parvum* and early wetzelielloid (*Vallodinium?* sp.) excursion provide Late Palaeocene – Early Eocene Period (~56–53 Ma) for the dinocyst interval in the middle part of the section. A pronounced negative Carbon Isotope Excursion (CIE) in the middle part is correlated to the second Eocene Thermal Maximum (53.7 Ma), which is a globally recorded hyperthermal event. During the ETM–2 warming, the rise in pCO_2 caused warm, humid conditions as well as a rise in sea level, which may have contributed to the establishment of constrained shallow marine environments in the examined middle unit sedimentary succession. Floral (spore–pollens, leaf, wood, seed, fruits) and faunal assemblages (Crocodiles, fish remains, amber insects) revealed the prevalence of a dense tropical luxurious rain forest (floral and faunal) near shore during the ETM–2 in the Tarkeshwar Lignite Mines, Cambay Basin.

Key–words—Amber, Cambay Basin, Floral Assemblage, Eocene, Gujarat, Palaeoenvironment, Vertebrate fauna.

INTRODUCTION

OVER the past two decades, evidences on the early development of vertebrates and biotic radiations during the Early Eocene have been abundantly studied from the sedimentary depositions of the Cambay Shale Formation exposed in the lignite mines at Vastan, Tarkeshwar and Mangrol (Rana *et al*., 2004; Rage *et al*., 2008; Prasad *et al*., 2013; Smith *et al*., 2016). Situated in a palaeo–equatorial setting during the Early Palaeogene, the Cambay depositions are a significant source to comprehend equatorial climate shifts and hyperthermal events including the Palaeocene–Eocene Thermal Maximum (Samanta *et al*., 2013a, b). Major palaeontological work, specifically vertebrates, and their implications on fossil history have been well recorded from the Vastan Lignite Mine, Cambay Basin (Bajpai *et al*., 2005a, b, 2006 a, b, 2009a, b; Punekar & Saraswati, 2010; Clementz *et al*., 2011; Folie *et al*., 2012). Significant work from the Tarkeshwar Lignite Mine covers palaeobotanical, petrological, and palaeontological studies (Singh *et al*., 2014, 2016, 2019, 2021; Nagori *et al*., 2013; Rust *et al*., 2010; Grimaldi *et al*., 2013; Engel *et al*., 2011, 2013). Exceptional research by Smith *et al*. (2016) from the Tarkeshwar Lignites found the existence of a significant diversity of vertebrate species that have affinities to both Laurasian European and Gondwana (e.g., the Pelomedusoides turtle, a dyrosaurid crocodyliform,

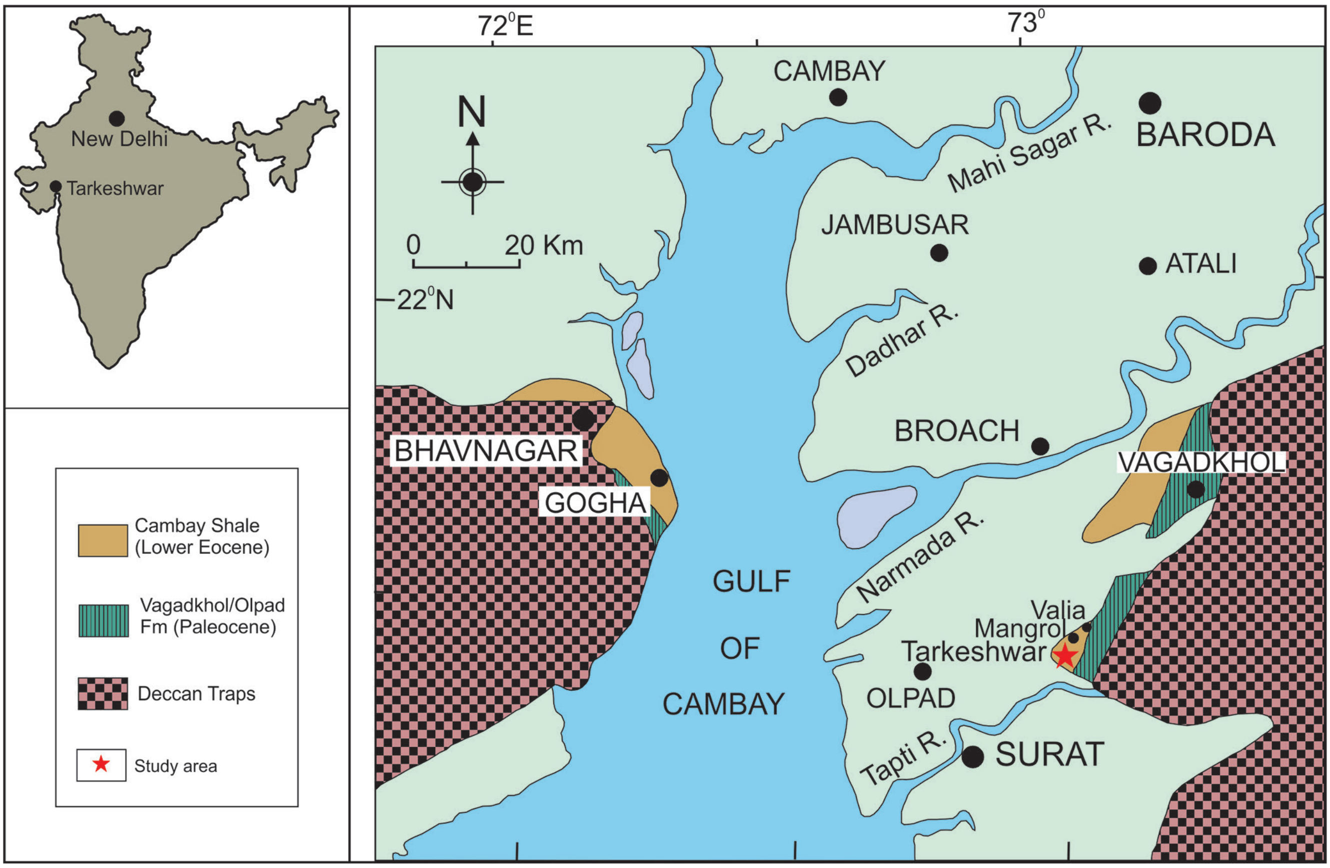

Fig. 1—Location map of Tarkeshwar Lignite Mine (Cambay Basin), Gujarat, India (after Sahni *et al*., 2006).

and a big madtsoiid snake, trionychoid turtles, the bats, the adapoid primates, and the ailuravine rodent) suggesting post collision event. The study highlights the potential of the Tarkeshwar Lignite Mine in the field of vertebrate fauna and its connection to the post collision migration history.

Dinoflagellate cysts from the intercalated shales associated with the lignites offers valuable information on the age and palaeoenvironmental conditions (Garg *et al*., 2008; Prasad *et al*., 2013). In the present study, we have documented the Early Eocene biotic assemblage (Figs 3–4, 7–8) including dinoflagellate cysts, pollen/spore from lignite, associated sediments and amber and vertebrate remains from the Tarkeshwar Lignite Mine of the Cambay Basin, to highlight the biodiversity and palaeoenvironmental conditions during the time of deposition. This multidisciplinary (palaeobotanical, palaeontological, palaeoentomological) approach highlights the mode of deposition, climatic alterations and marine incursions within a coal forming system close to shore.

GEOLOGY OF STUDY AREA

The deposition of the Tarkeshwar Lignite Mine, south of Vastan (Latitude 21º 22' 33" N and Longitude 73º 07' 34" E) Lignite Mine consists of sandstones, bentonitic and carbonaceous clays and lignite beds of variable thickness (Singh *et al*., 2012). The sedimentary successions are attributed to the Cambay Shale, overlying the Palaeocene–Early Eocene Vagadkhol Formation, underlying the Eocene Nummulitic limestone and marl bed of the Amarawati Formation (Sudhakar & Basu, 1973). The Nummulitic Limestones overlying the topmost lignite seam at appear to be Middle Eocene based on the ostracod assemblages described from the clays and marls overlying the thick lignite seams (Nagori *et al*., 2013). The mine's sedimentary beds have in general the same pollen assemblages (Samant *et al*., 2014) known from the Vastan Mine (Rao *et al*., 2013), grouped under the Cambay Shale of Ypresian age.

Tarkeshwar has the nearly similar stratigraphic framework as the Vastan section. However, there exist some differentiations. The Nummulitic Limestone occurs above the topmost lignite (Sahni *et al*., 2006; Nagori *et al*., 2013) and is younger than the one at Vastan while the Lower Eocene marker foraminifer *N. burdigalensis burdigalensis* lies below it (Sahni *et al*., 2006). Another difference is the presence of two mammalian yielding beds at Tarkeshwar, while Vastan has only one. However, the *Nummulites* assemblage has yet to be fully investigated.

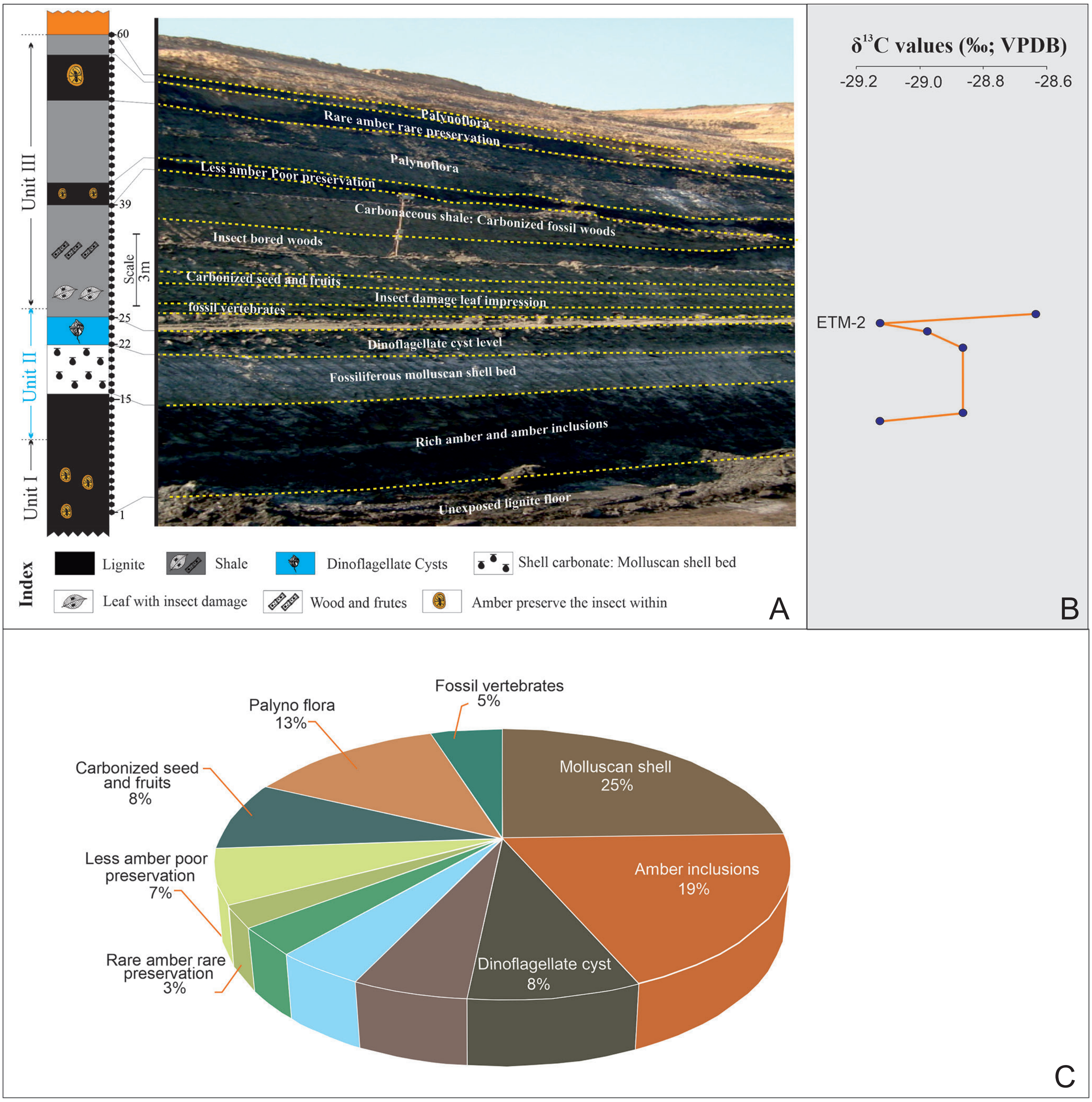

Fig. 2—Overall view and analysis of the field data from sedimentary beds of Tarkeshwar Lignite Mine. (A). Lithological section of the opencast Lignite Mine (southern pit), (B). δ^{13}C values of sample profile from where dinoflagellate cysts and amber biota were recovered, indicates ETM–2, (C). Percentage of the recovered biota from these sedimentary beds.

The Tarkeshwar lignites are rich in huminite, alongside different proportions of associated mineral matter (Singh *et al.*, 2012). The mineral suggests the formation of the lignite from a vegetal source, i.e. broad–leaved woody forest vegetation, herbs and shrubs. The composition of macerals is indicative of the deposition of lignite in sub–aqueous conditions with intermittent exposure and subsidence of the peat surface.

MATERIAL AND METHODOLOGY

The sedimentary shale and lignite samples have been recovered from the Tarkeshwar Lignite Mine (south pit), Surat (Gujarat). Sixty sediment samples of shale, lignite, and associated amber were collected from each stratigraphic sequence (Figs 1, 2). They were treated with hydrochloric

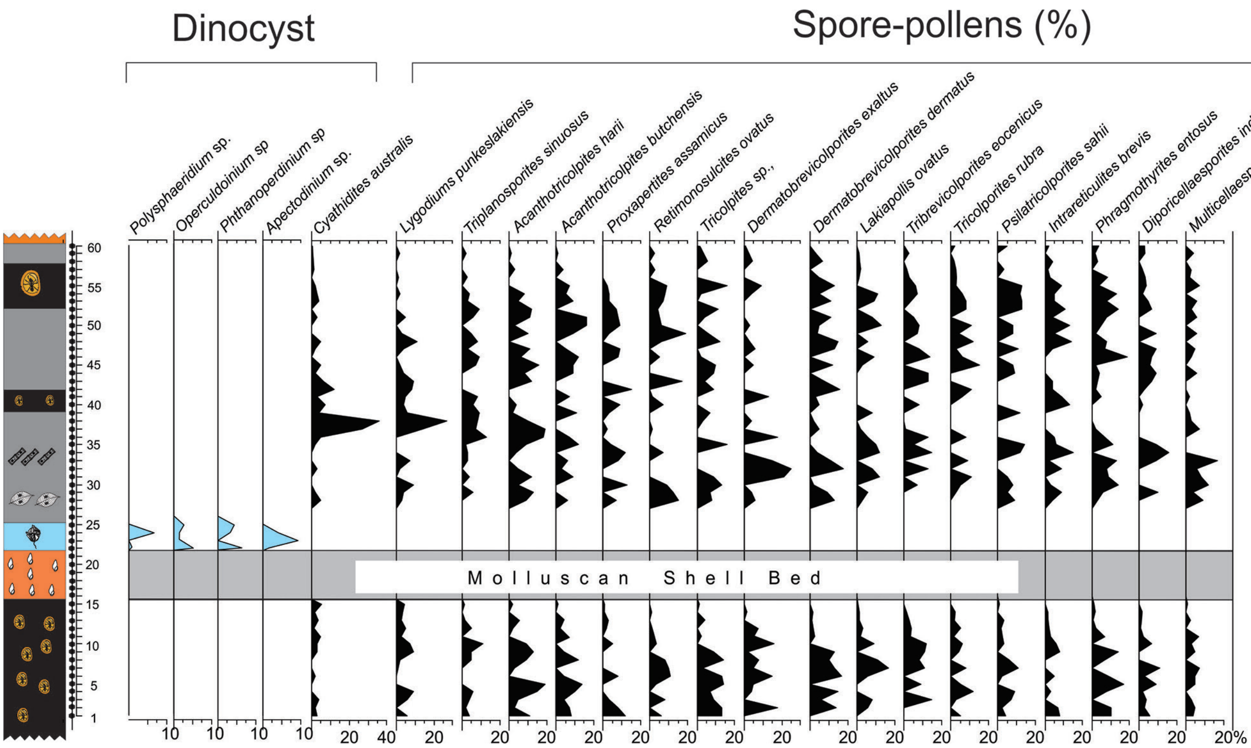

Fig. 3—Assemblage spectrum of palynomorphs, Tarkeshwar Lignite Mine.

acid, hydrogen fluoride and diluted nitric acid for 3–4 days with intermittent washing. The acid–free samples were sieved through 20–micron mesh. Slides were prepared using polyvinyl alcohol, mounted by Canada balsam. Amber inclusions from the lignite seams were grounded and polished via emery sheets. The overall taxonomy follows DINOFLAJ3 (Williams *et al*., 2017). The specimens were examined under Leica M 205A stereoscope attached to a Leica DM 6000 Digital Camera and Leica Application Suite LAS 3.7. Terminologies follow Slipinski 2007, Lawrence *et al*. 2011 and Szawaryn 2019.

For isotopic profiles, all the samples were powdered and treated with 5% HCl to remove carbonate. Subsequently, acid and soluble salts were removed from the sediments by centrifuging at 3000 rpm and dried in an oven at 50º C and later crushed to fine powder. All the powdered and weighed samples were individually introduced into the pre–filled and conditioned reactor of Elemental Analyzer (Flash EA 2000 HT) through an auto sampler. The sample CO_2 gas produced during combustion was introduced into MAT 253 Continuous Flow Isotope Ratio Mass Spectrometer (CFIRMS) coupled with ConFlow IV interface. Signals corresponding to masses 44, 45 and 46 were measured for both sample and a reference gas, thereby calculating the isotopic (Fig. 2b) compositions of individual samples. Reproducibility was also checked by repeat measurements. The tank CO_2 was calibrated using international standard IAEA CH–3. The long–term uncertainties associated with stable isotope analysis was 0.1‰ (1σ).

RESULTS

Palynological analysis reveals the abundant organic matter including spore–pollen, cuticles (Fig. 5a–t) dinoflagellate cysts (Fig. 6a–f) and marine remains (foraminiferal test linings, (Fig. 6g–h) present in the studied section. Besides microfossils, megafossils like woods, arthropods like terrestrial ants and nematoceran flies and vertebrate fragments like fish teeth have also been documented (Fig. 8c–d). The studied successions are differentiated into the basal lignite unit, middle shale unit and the topmost lignite unit. Dinoflagellate cysts occur in the middle part whereas both basal and topmost lignite units are devoid of dinocysts. Even though the cysts are in less abundance (less than 10 in each sample), they are valuable in defining the age and palaeoenvironmental parameters. Dinoflagellate cysts assemblage consists of species *Polysphaeridium* sp., *Spiniferites* sp., *Lejeunecysta* sp., *Apectodinium longispinosum*., *Apectodinium parvum* (atypical), *Phthanoperidinium* sp. Strikingly it also includes early wetzelloidian species *Epellidinium?* sp. (Fig. 6a–f). Stratigraphic ranges (first appearance datum–FAD & last appearance datum–LAD) of the documented taxa are provided in Fig. 6.

Palynofloral assemblage recorded from the Tarkeshwar sedimentary strata (Fig. 5a–t) includes *Cyathidites australis, Lygodiumsporites lakiensis, Triplanosporites sinuosus, Acanthotricolpites karii, Acanthotricolpites intermedius, Proxapertites assamicus, Retimonosulcites ovatus, Tricolpites* sp., *Dermatobrevicolporites exaltus*, *Dermatobrevicolporites*

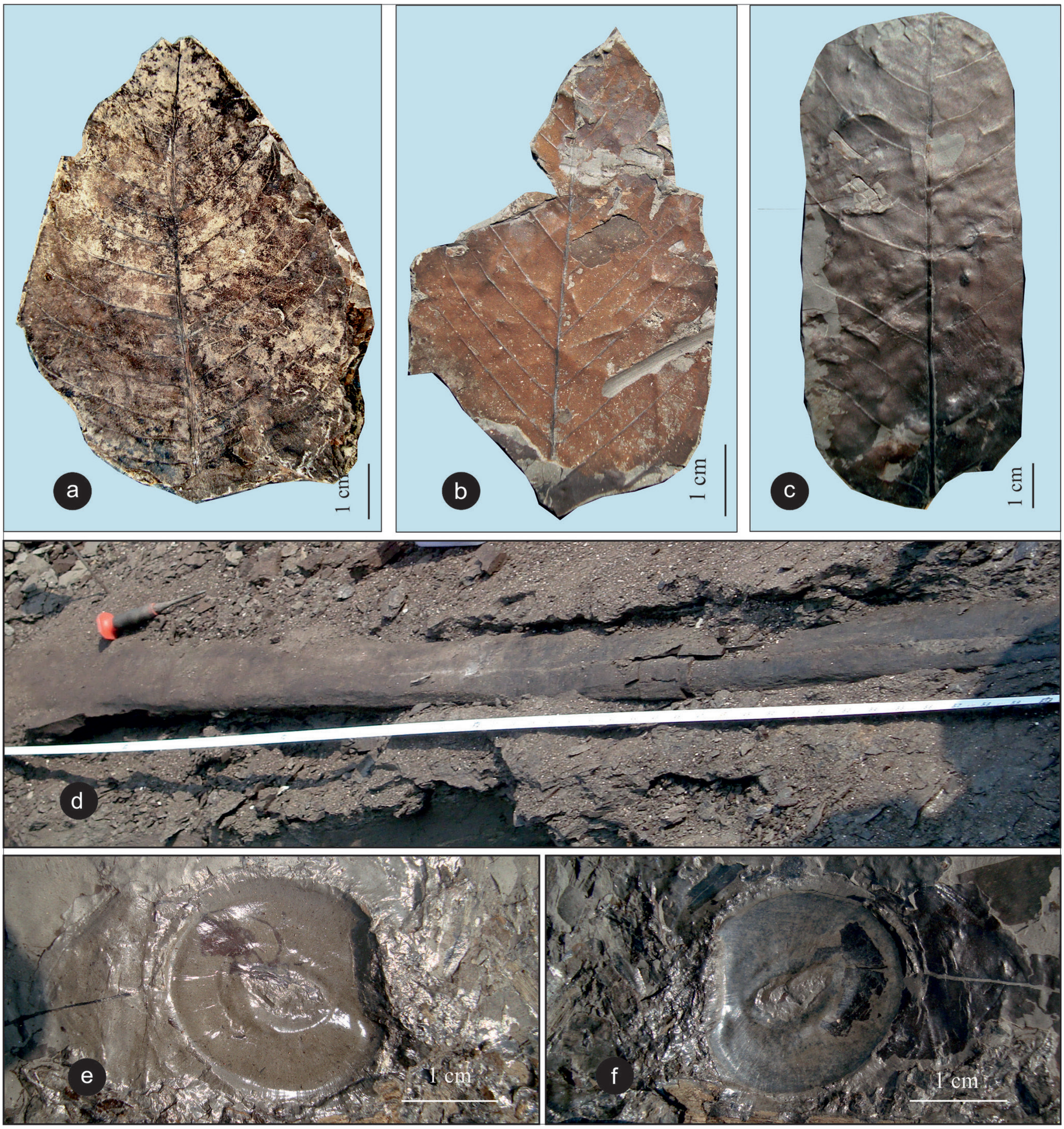

Fig. 4—Field data from the sediment beds viz. fossil leaves, woods, fruits and seeds of Tarkeshwar Lignite Mine.

dermatus, Lakiapollis ovatus, Tribrevicolporites eocenicus, Tricolporites rubra, Psilatricolporites sahii, Intrareticulites brevis, Phragmothyrites eocenicus, Diporicellaesporites indicus and *Multicellaesporites prakashii*. Temporal variation in the palynofloral assemblages of the studies sections are displayed (Figs 5, 7). The basal part consisting of samples 1–19 is mainly dominated by pteridophytic (*Cyathidites australis* and, *Lygodiumspunkes lakiensis*) and fungal spores followed by tropical rainforest and very low abundance of mangrove taxa (*Proxapertites*). Middle of the basal sequence is composed of high relative abundances of *Spinizonocolpites* and *Proxapertites,* with an overall high abundance of pollen. The top part consists overall low abundance of overall pollen and the taxa is mainly represented by to tropical rainforests and fungal elements (Figs 5, 7). Sediment analysis for vertebrate fossils (Fig. 8c–h) revealed elasmobranch teeth of *Physogaleus secundus,* Crocodile teeth and Myliobatidae fish teeth remains which are also reported earlier from the Cambay Shale F ormation.

Amber inclusions from the Tarkeshwar Lignites documents fossilized flying and terrestrial group of insects including ant families (Formicidae; Fig. 8a) and non–biting midges (Chironomidae) (nymph; Fig. 8b). Tarkeshwar Lignites exhibits similar analogue to present day extant resin flows in New Caledonia (Sadowski *et al*., 2012). The most significant aspect of Cambay amber is the diversity of social insects, incorporating bees, ants and the earliest Rhinotermitidae from the Vastan and Tarkeshwar Lignite Mines, whose oldest fossil dates from the Miocene (Engel *et al*., 2011, 2013). The Tarkeshwar Mine also holds records of distinctive flower groups like Apocynaceae, observed by micro–CT scanning and epiflourescence microscopy (Singh *et al*., 2021). Cambay amber insect species show phylogenetic connections with those from northern Europe's Eocene, notably Baltic amber.

DISCUSSION

Present study from the Tarkeshwar Lignite Mine helps to understand the palynological assemblages, i.e. pollen–spores and dinoflagellate cysts. The percentage of dinoflagellate cysts is quite low in the Cambay but is of crucial significance in the age dynamics, climate and associated depositional palaeoenvironments discussed below:

Biotic components and stratigraphic setup

The Tarkeshwar Lignite Mine consists two lignite units, namely the topmost (lignite–1) and the basal (lignite–2), sandwiching a unit of shale. Palaeontologists are primarily concerned in the shale unit between the lignites age because it has a variety of vertebrate fauna that have been found at Tarkeshwar (Smith *et al*., 2016). Dinoflagellate cysts yielded in the shale unit between the two lignite unit consist significant taxa allowing age assignment for the top of the basal lignite. *Apectodinium longispinosum*, *Apectodinium parvum* and early wetzelielloid species *Epillidinium* sp. are crucial to assign age for the studied section. *Apectodinium longispinosum* and *Apectodinium parvum* both has its FAD in the latest Thanetian (NP9 biozone) and range up to early Ypresian. *Apectodinium parvum* range from the latest Thanetian to early Ypresian age (Np9–Np 11). *Apectodinium parvum* (atypical) is different from typical forms by the larger size of cyst and more developed apical, lateral and antapical horns. Atypical *A. parvum* is also documented from the Paris and Dieppe basins during the Early Eocene time period corresponding to the PETM (Iakovleva *et al*., 2021). In the Tethys region, *Apectodinium longispinosum* is reported from late Thanetian–Ypresian in the Meghalaya region (Np9?–Np11), and Salt range, Punjab, Pakistan (Np10) (Kothe, 1988; Garg & Ateequazaman, 2000). The earliest wetzielloids have been recorded from the Eastern Tethys sea (Kazakhsthan region) during the PETM (Iakovleva, 2017) and from the Early Eocene in the Jathang Section, Lakadong sandstone, Meghalaya and Naredi formations, Kutch Basin (Prasad *et al*., 2018; Garg *et al*., 2011). This assemblage, thus, suggests that the marine incursion above the basal lignite in the Tarkeshwar occurred during the late Thanetian to early Ypresian corresponding to SBZ 4/5 to SBZ 8 (Fig. 6) probably during the Palaeocene–Eocene Thermal Maximum. Previously Samanta *et al*., 2013a reported Early Eocene hyperthermal events from the Vastan, in which the PETM is reported below the mammal bearing horizon. Khozyem *et al*., 2021 studied the Carbon isotope stratigraphy from the Tarkeshwar Mine and found the negative excursion in the basal lignite which is assigned to the PETM. This supports the age assignment of late Thanetian to early Ypresian during the PETM (55.6–55.9 Ma, Gradstein *et al*., 2020).

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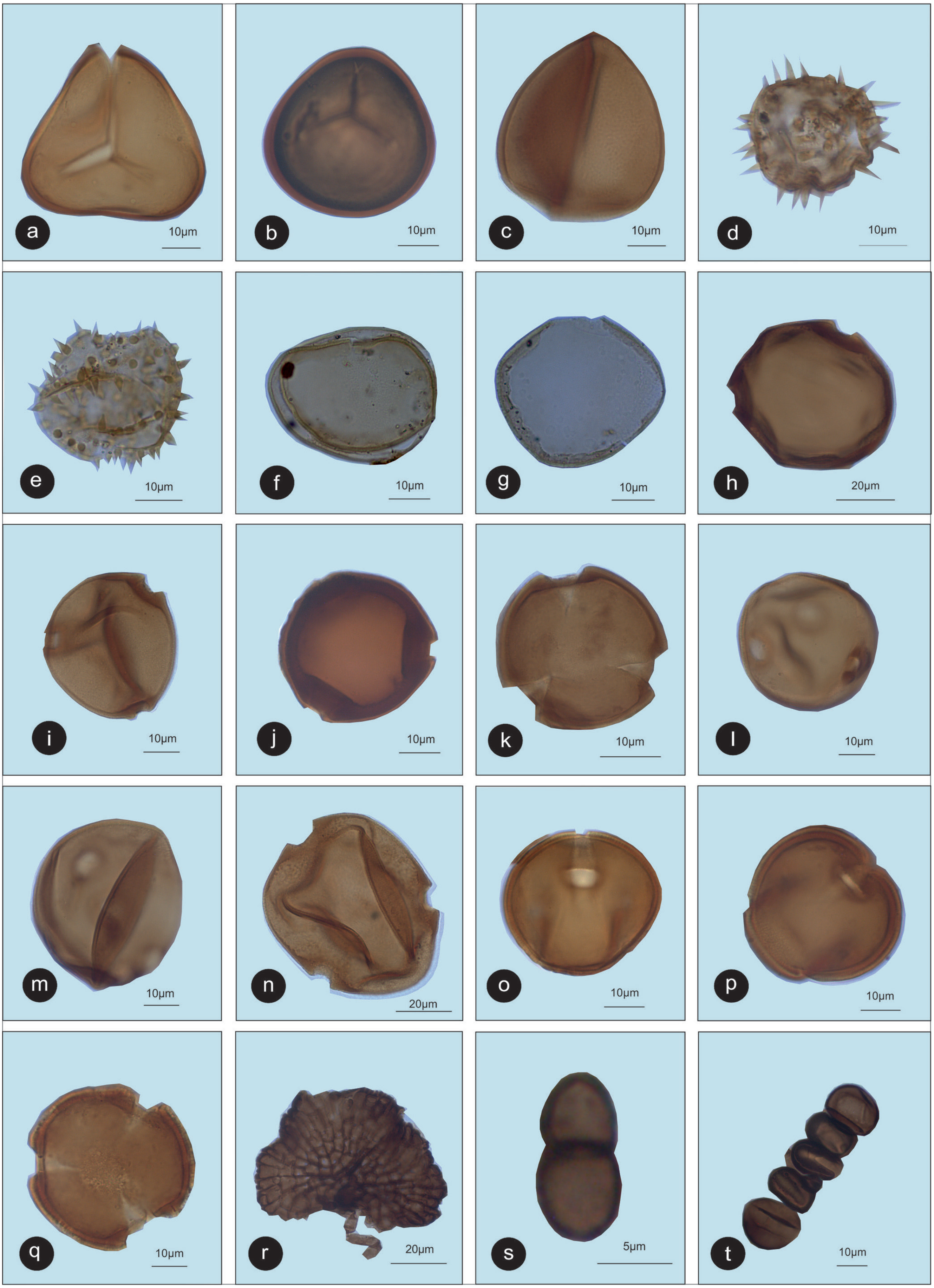
Fig. 5—(a) *Cyathidites australis* Couper 1953, BSIP Museum Slide No. 16954, (b) *Lygodiumsporites lakiensis* Sah & Kar 1969, BSIP Museum Slide No. 16950, (c) *Triplanosporites sinuosus* Samant & Phadtare 1997, BSIP Museum Slide No. 16953, (d) *Acanthotricolpites karii* Saxena & Khare 2004, BSIP Museum Slide No. 16948, (e) *Acanthotricolpites intermedius* Singh & Misra 1991, BSIP Museum Slide No. 16948, (f) *Proxapertites assamicus* Singh 1975, BSIP Museum Slide No. 16948, (g) *Retimonosulcites ovatus* Kar 1985, BSIP Museum Slide No. 16948, (h) *Tricolpites* sp.*,* BSIP Museum Slide No. 16953, (i) *Dermatobrevicolporites exaltus* Kar 1985, BSIP Museum Slide No. 161156, (j) *Dermatobrevicolporites dermatus* (Sah & Kar) Kar 1985, BSIP Museum Slide No. 16952, (k) *Dermatobrevicolporites dermatus* (Sah & Kar) Kar 1985, BSIP Museum Slide No. 16957, (l) *Lakiapollis ovatus* Venkatachala & Kar 1969, BSIP Museum Slide No. 16952, (m) *Lakiapollis ovatus* Venkatachala & Kar 1969, BSIP Museum Slide No. 16952, (n) *Tribrevicolporites eocenicus* Kar 1985, BSIP Museum Slide No. 16953, (o) *Tricolporites rubra* (Dutta & Sah) Tripathi & Singh 1985, BSIP Museum Slide No. 16951, (p) *Psilatricolporites sahii* Saxena & Khare 2004, BSIP Museum Slide No. 16953, (q) *Intrareticulites brevis* (Sah & Kar) Kar 1985, BSIP Museum Slide No. 16955, (r) *Phragmothyrites entosus* (Dilcher) Kar & Saxena 1976, BSIP Museum Slide No. 16951, (s) *Diporicellaesporites indicus* Gupta 2002, BSIP Museum Slide No. 16948, (t) *Multicellaesporites prakashii* Ambwani 1982, BSIP Museum Slide No. 16949.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Previous studies from the northern pit of the Tarkeshwar Lignite Mine also revealed very low abundances of dinocysts and diversity (no. of species) recovered are higher as compared to the present study which includes the species *Apectodinium homomorphum*, *Apectodinium longispinosum*, *Cleistosphaeridium diversispinosum*, *Glaphyrocysta exuberans*, *Hystrichokolpoma granulatum, Hystrichokolpoma manipulatum*, *Melitasphaeridium pseudorecurvatum* and *Polysphaeridium subtile* in which *Polysphaeridium subtile* was found dominant in few intervals indicating restricted marine setting (Steeman, 2020). Though few species are absent in the present study as compared to Steeman, 2020 presence of *Apectodinium* suggests similar environmental conditions between southern and northern pit of the Tarkeshwar Lignite Mine. It is also found that very less abundance of dinoflagellate cysts are due to the high dilution by phytoclasts with high influx of terrestrial material due to increased runoff due to the warming occurring during the Palaeocene–Eocene boundary.

The dinoflagellate cysts assemblages show barely any resemblance between the Vastan Lignite Mine (Garg *et al*., 2008) which is adjacent to the Tarkeshwar Lignite Mine (~8 Km north) and shows no presence of *Apectodinium*. Despite the absence of *Apectodinium augustm* Garg *et al*., 2008 assigned Vastan succession–A to the Aau dinocysts biozone (Powell, 1992). Presence of *Apectodinium* in the Tarkeshwar supports the presence of Aau biozone in the Cambay Shale. Besides the observed barely any overlap between the Vastan and Tarkeshwar suggests poor lateral continuity and changes in the depositional and palaeoenvironments between the two sites. The very low abundances of cysts also point to the deposition of cyst intervals in a very restricted shallow environment influenced by high runoff environments and low saline conditions. It is not surprising that in restricted marine settings (e.g., estuaries, bays) dinocyst distribution shows variation in small spatial scales as governed by freshwater vs sea water influences and nutrients (Thakur *et al*., 2015).

Dinocyst genus *Apectodinium* indicates prevalence of warm and nutrient rich or eutrophic conditions. Dominance of peridinioid taxa over gonyalaucoid autotrophic taxa indicates abundant nutrients and freshwater discharge showing high productivity in the studied area. The presence of *Phthanoperidinium* also reveals that nutrient input could probably have been related to the freshwater influence. High abundances of *Polyspaheridium subtile* suggest deposition in a nearshore very restricted environment with seasonal fluctuations. The studied succession of the Cambay Shale is likely to be deposited in a near shore setting with an episode of marine transgression.

$\delta^{13}C$ values of samples in the Tarkeshwar profile

Globally, several hyperthermal events have been recorded in the early Palaeogene (~55.7–52.8 Ma) e.g. Palaeocene–Eocene Thermal Maximum (PETM), ETM–2, H1, H2, I1, and I2 (Dickens *et al*., 1995, 1997). These hyperthermal events were characterized by rapid addition of ^{12}C enriched carbon into the atmosphere and rapid burial of ^{12}C enriched organic matter into the sediments (Bowen & Zachos, 2010). Therefore, the carbon isotopic compositions ($\delta^{13}C$ values) of organic matter associated sedimentary sequences are used to identify hyperthermal events through negative carbon isotope excursion (CIE). In the present study, the $\delta^{13}C$ values of samples in the Tarkeshwar profile vary in narrow range and range from–29.2 to–28.6 ‰, suggesting a Lower Eocene sedimentary profile, concordant with the Lignite mines of the Cambay Basin. The lowest $\delta^{13}C$ value (–29.2 ‰) observed in the shale unit (Fig. 8). Tarkeshwar Mine samples are characterized by more negative $\delta^{13}C$ values with maximum lowering observed in the shale unit (–29.2 ‰). Such lower $\delta^{13}C$ values suggest higher input of ^{12}C enriched CO_2 in the atmospheric carbon pool which lower the $\delta^{13}C$ values of organic matter. Therefore, it can be suggested that lower isotopic value recorded in the shale represent a short–term carbon cycle perturbations. But, more detailed investigations and isotopic analysis are necessary to identify the exact hyperthermal events.

Palynofloral Data and Palaeocene–Early Eocene Ecosystem

The floral assemblages are dominated by angiosperm pollen taxa over pteridophytes spores and fungal remains. The basal part consists of diversified pollen flora suggesting deposition in the marsh/swamp environment with dominance of tropical evergreen forest. The middle unit consists of relatively high abundance of *Nypa* (*Spinizonocolpites*) and *Proxapertites* which belongs to Arecaceae (Palmae).

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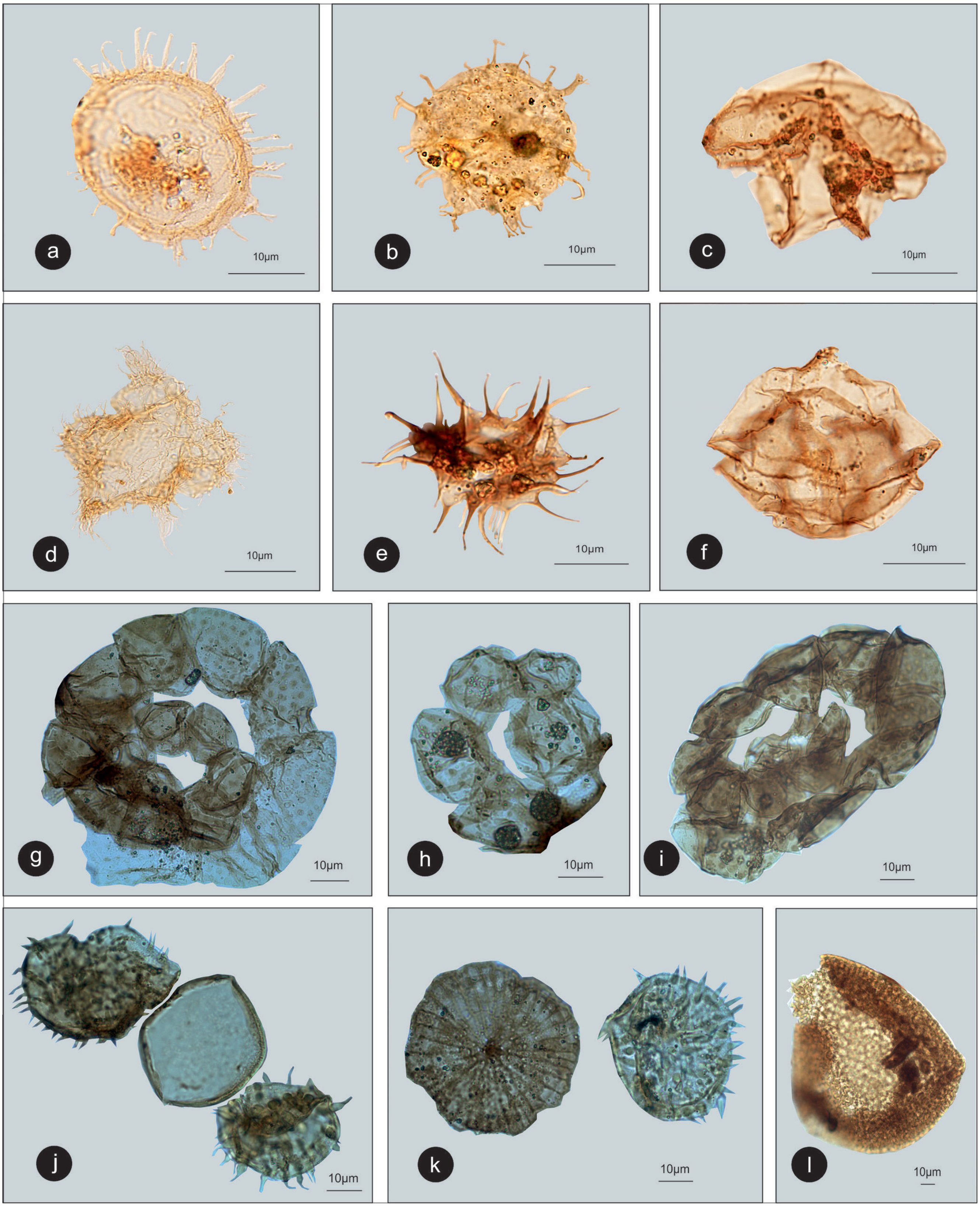
Fig. 6—(a) *Polysphaeridium* sp. BSIP Museum Slide No. 16959A, (b) *Spiniferites* sp., BSIP Museum Slide No. 16959B, (c) *Lejeunecysta* sp. BSIP Museum Slide No. 16948, (d) *Apectodinium* sp. BSIP Museum Slide No. 16960, (e) ?*Selenopemphix armata* Museum Slide No. 16948, (f) *Phthanoperidinium* sp. Museum Slide No. 16948, (g–i) Foraminiferal linings, BSIP Museum Slide No.16961, (j) *Spinizonocolpites echinatus/Proxapertites reticulatus* (Arecaceae affinity), BSIP Museum Slide No. 16962, (k) *Phragmothyrites eocenicus* fungal remain and *Spinizonocolpites echinatus* (Arecaceae affinity), BSIP Museum Slide No. 16963, (l) *Matanomadhensis kutchensis* (Annoniaceae affinity), BSIP Museum Slide No. 16963.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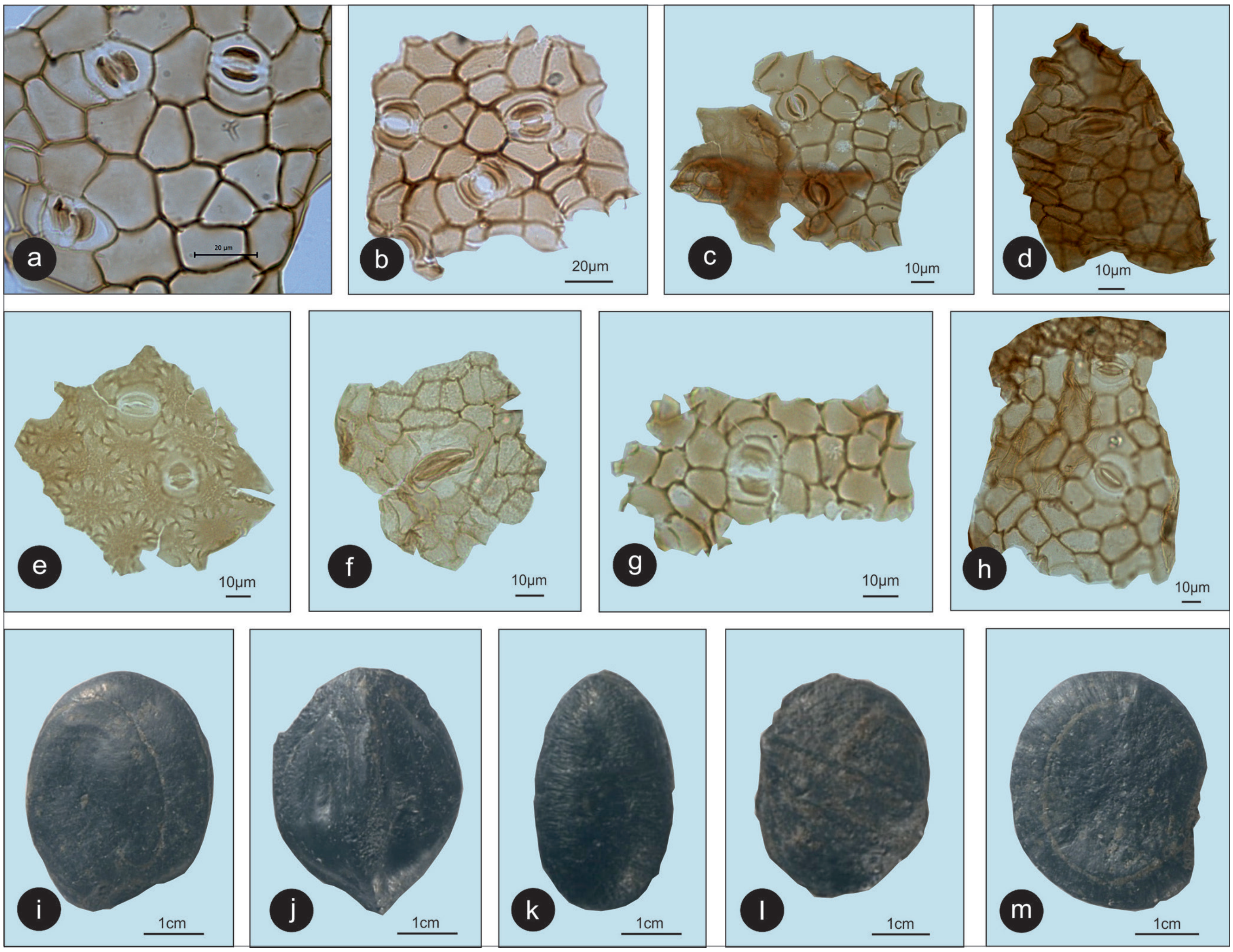

Fig. 7—(a–h) Recovered varied stomata structures through laboratory chemical processed, (a–d) Leaf stomata, BSIP Museum Slide No. 16964, (e–h) Leaf stomata, BSIP Museum Slide No. 16965. Fossil fruits investigated in the field of sedimentary bed (i) Fossil seed, BSIP Museum Specimen No. 41986, (j) Fossil seed, BSIP Museum Specimen No. 41987, (k) Fossil seed, BSIP Museum Specimen No. 41988, (l) Fossil seed, BSIP Museum Specimen No. 41989, (m) Fossil fruit, BSIP Museum Specimen No. 41990.

Arecaceae are predominantly pantropical in distribution with major habitats in evergreen to semi–evergreen forests. Dominance of mangrove taxa (including *Spinizonocolpites*, *Proxapertites*) infers deposition near to the seashore. Pollen assemblage from the topmost unit indicates families belonging to tropical rainforest vegetation. Abundant fungal spores and angiospermic pollen taxa also reveal the prevalence of tropical evergreen rain forest.

The presence of Microthyriaceous fungal remains reveals deposition in the tropical environment with heavy rainfall. The Arecaceae plant family, pan–tropical to equatorial zone plant family indicates of humid and warmer conditions during the depositional time period. Although, limitation of biostratigraphy cannot provide information on time span for a specific type of forest, but the evergreen and semi–evergreen nature of the forest suggest a warm and humid climate during the Early Eocene (Prasad *et al*., 2009; Jaramillo *et al*., 2010). The warm climate providing more precipitation results in the proliferation of tropical evergreen forests. The hyperthermal events occurred during the Late Palaeocene to Early Eocene altered hydrological cycle increased precipitation which lead to the development of tropical rainforest in an equatorial setting. Presence of Dipterocarpaceae pollen infer about the seasonally wet conditions (Jaramillo *et al*., 2010). The occurrence of amber inclusions marks the dry season with high production of resin during the depositional period alongside leaf cuticles and pollen assemblage.

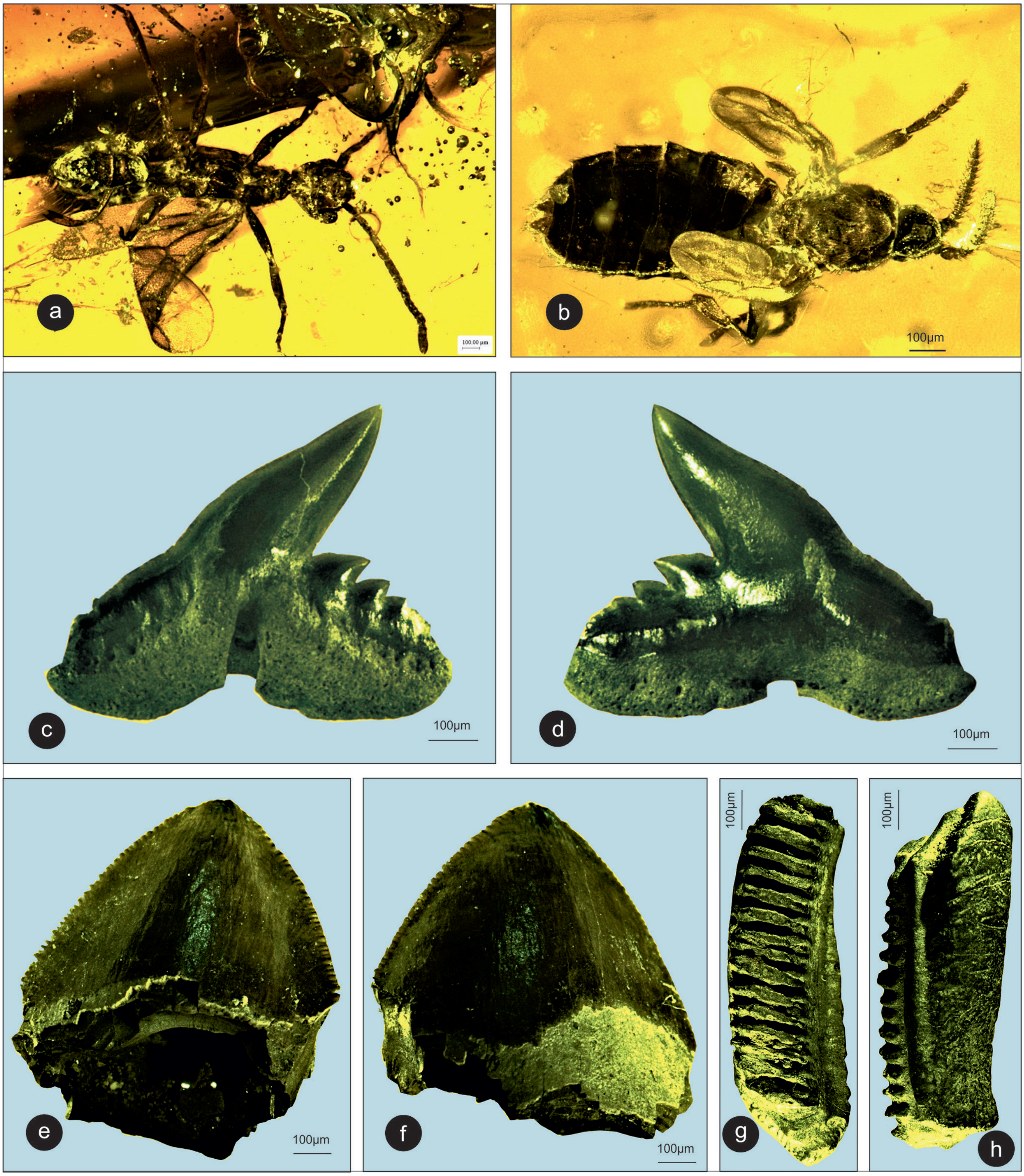

Fig. 8—Amber trapped insect taxa: (a) Ant (Formicidae) BSIP Museum Specimen No. 41991, (b) Midge (nymph), BSIP Museum Specimen No. 41992, (c–d) Sediment recovered elasmobranch teeth of *Physogaleus secundus* (lingual & labial view) BSIP Museum Specimen No. 41993, (e–f) Dorsal and ventral both (sides) view of the Crocodile teeth, BSIP Museum Specimen No. 41994, (g–h) Dorsal and ventral both (sides) view Myliobatidae fish teeth, BSIP Museum Specimen No. 41995.

Apart from that, presence of Elasmobranchian (*Physogaleus secundus*), Myliobatidae fishes and Crocodile teeth reveals about the existence of amphibian (reptiles) near the depositional site. The semi–aquatic crocodile favours coastal salt water lagoons to fresh water habitats and may even is found in brackish water environments. On the contrary, the Elasmobranchian (*Physogaleus secundus*) and Myliobatidae fish teeth sustain the condition to be of a marine setting. Insect inclusions in amber resin like the eusocial ants and midges suggest diversified ecosystem which radiated during Palaeocene–Eocene. Present study also supports the evidences of evolution of these eusocial insects during Palaeocene–Eocene, probably in relation to the warming.

CONCLUSION

The Early Eocene palaeobiotic forms of the Tarkeshwar Lignite Mine (Gujarat, India) draws attention on the following points of conclusion:

1. Dinoflagellate cysts abundance and diversity is very low but consists of some significant age marker taxa suggesting late Thanetian to early Ypresian age for the deposition. Negative Carbon Excursion further suggests ETM–2 event in the studied section.
2. Palynological assemblage reveals similarity between the Vastan and Tarkeshwar Lignite Mines and presence of warm and humid conditions during ETM–2.
3. Lignite and shale dominated Cambay deposition occurred in near shore terrestrial environment with shallow marine conditions (coastal environment) during Late Palaeocene–Early Eocene (~55.5–52 Ma).
4. Lower $\delta^{13}C$ values imply a greater input of ^{12}C enriched CO_2 into the atmosphere's carbon pool, lowering organic matter's $\delta^{13}C$ values. As a result, it is possible to infer that the decreased isotopic values found in the shale imply short–term changes to the carbon cycle.
5. Present study records a diverse ecosystem with well–preserved vertebrate fauna, amber biota, and associated sedimentary terrestrial and coastal biotic elements suggesting seasonal variations during the Eocene.
6. Present study provides comprehensive picture of mega and microfossils with faunal, floral and isotope records preserved during ETM–2 in the Tarkeshwar Ligine deposits (Cambay Basin).

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REFERENCES

Bajpai S, Kapur VV, Das DP, Tiwari BN, Saravanan N & Sharma R 2005a. Early Eocene land mammals from the Vastan Lignite Mine, District Surat, Gujarat, western India. Journal of the Palaeontological Society of India 50(1): 101–113.

Bajpai S, Kapur VV, Thewissen JGM, Das DP, Tiwari BN, Sharma R & Saravanan N 2005b. Early Eocene primates from Vastan Lignite Mine, Gujarat, western India. Journal of the Palaeontological Society of India 50: 43–54.

Bajpai S, Kapur VV, Thewissen JGM, Das DP & Tiwari BN 2006a. New Early Eocene cambaythere Perissodactyla, Mammalia from the Vastan Lignite Mine Gujarat, India and an evaluation of cambaythere relationships. Journal of the Palaeontological Society of India 51(1): 101–110.

Bajpai S, Thewissen JGM, Kapur VV, Tiwari BN & Sahni A 2006b. Eocene and Oligocene Sirenians Mammalia from Kachchh, India. Journal of Vertebrate Palaeontology 26(2): 400–410.

Bajpai S, Kapur, VV & Thewissen JGM 2009a. Creodont and condylarth from Cambay Shale Early Eocene ~55–54 Ma, Vastan Lignite Mine, Gujarat, western India. Journal of the Palaeontological Society of India 54: 103–109.

Bajpai S, Thewissen JGM & Sahni A 2009b. The origin and early evolution of whales: macroevolution documented on the Indian Subcontinent. Journal of Biosciences 34: 1–13.

Bowen GJ & Zachos JC 2010. Rapid carbon sequestration at the termination of the Palaeocene–Eocene Thermal Maximum. Nature Geoscience 3: 866–869.

Clementz M, Bajpai S, Ravikant V & Thewissen JGM, Saravanan N, Singh IB & Prasad V 2011. Early Eocene warming events and the timing of terrestrial faunal exchange between India and Asia. Geology 391: 15–18.

Dickens GR, Castillo MM & Walker JCG 1997. A blast of gas in the latest Paleocene: simulating first–order effects ofmassive dissociation of oceanic methane hydrate. Geology 25(3): 259–262.

Dickens GRO, Neil JR, Rea DK & Owen RM 1995. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. Paleoceanography 10: 965–971.

Engel MS, Grimaldi DA, Nascimbene PC & Singh H 2011. The termites of Early Eocene Cambay amber, with the earliest record of the Termitidae Isoptera. ZooKeys 148: 105–123.

Engel MS, Ortega–Blanco J, Nascimbene P & Singh H 2013. The bees of Early Eocene cambay amber Hymenoptera: apidae. Journal of Mellitology 25: 1–12.

Folie A, Rana RS, Rose KD, Sahni A, Kumar K, Singh L & Smith T 2012. Early Eocene frogs from Vastan Lignite Mine, Gujarat, India. Acta Palaeontologica Polonica 58(3): 511–524.

Garg R & Ateequzzaman K 2000. Dinoflagellate cysts from the Lakadong Sandstone, Cherrapunji area: biostratigraphical and palaeoenvironmental significance and relevance to sea level changes in the Upper Palaeocene of the Khasi Hills, South Shillong Plateau, India. Palaeobotanist 49(1–3): 461–484.

Garg R, Ateequzzaman K, Prasad V, Tripathi SKM, Singh IB, Jauhri AK & Bajpai S 2008. Age–diagnostic dinoflagellate cysts from the lignite–bearing sediments of the Vastan Lignite Mine, Surat District, Gujarat, western India. Journal of the Palaeontological Society of India 53: 99–105.

Garg R, Prasad V, Thakur B, Singh IB & Khowaja A 2011. Dinoflagellate cysts from the Naredi Formation, Southwestern Kutch, India: Implications on age and palaeoenvironment. Journal Palaeontological Society of India 56: 201–218.

Gradstein FM, Ogg JG, Schmitz MD & Ogg GM (Editors) 2020. Geologic time scale 2020. Elsevier.

Grimaldi D, Engel MS & Singh H 2013. Coniopterygidae Neuroptera: Aleuropteryginae in amber from the Eocene of India and the Miocene of Hispaniola. American Museum Novitiates 20133770: 20–39.

Iakovleva AI 2017. Did the PETM trigger the first important radiation of wetzelielloideans? Evidence from France and northern

Kazakhstan. Palynology 413: 311–338.

Iakovleva AI, Quesnel F & Dupuis C 2021. New insights on the Late Paleocene− Early Eocene dinoflagellate cyst zonation for the Paris and Dieppe basins. Bulletin de la Société Géologique de France 192: 1–18. https://doi.org/10.1051/bsgf/2021035.

Jaramillo C, Ochoa D, Contreras L, Pagani M, Carvajal–Ortiz H, Pratt LM, Krishnan S, Cardona A, Romero M, Quiroz L & Rodriguez G 2010. Effects of rapid global warming at the Paleocene–Eocene boundary on neotropical vegetation. Science 3306006: 957–961.

Khozyem H, Adatte T, Keller G & Spangenberg JE 2021. Organic carbon isotope records of the Paleocene–Eocene Thermal Maximum event in India provide new insights into mammal origination and migration. Journal of Asian Earth Sciences 104736. https://doi.org/10.1016/j.jseaes.2021.104736.

Köthe A 1988. Biostratigraphy of the Surghar Range, Salt Range, Sulaiman Range and the Kohat area, according to Jurassic through Paleogene calcareous nannofossils and Paleogene dinoflagellates: Geologisches Jahrbuch, pt. B71: 3–87.

Lawrence JF, Ślipiński A, Seago A, Thayer M, Newton A & Marvaldi A 2011. Phylogeny of the Coleoptera based on adult and larval morphology. Annales Zoologici 61: 1–217.

Nagori ML, Khosla SC & Jakhar SR 2013 Middle Eocene Ostracoda from the Tarkeshwar Lignite Mine, Cambay Basin, Gujarat. Journal of the Geological Society of India 81: 514–520.

Powell AJ 1992. Dinoflagellate cysts of the Tertiary System. A Stratigraphic Index of Dinoflagellate Cysts 155–251.

Prasad GVR, Verma O, Flynn JJ & Goswami A 2013. A new Late Cretaceous vertebrate fauna from the Cauvery Basin, South India: implications for Gondwanan paleobiogeography. Journal of Vertebrate Paleontology 33(6): 1260–1268.

Prasad V, Farooqui A, Tripathi SKM, Garg R & Thakur B 2009. Evidence of Late Palaeocene–Early Eocene equatorial rain forest refugia in southern Western Ghats, India. Journal of Biosciences 34: 777–797.

Prasad V, Utescher T, Sharma A, Singh IB, Garg R, Gogoi B, Srivastava J, Uddandam PR & Joachimski MM. 2018. Low–latitude vegetation and climate dynamics at the Paleocene–Eocene transition–a study based on multiple proxies from the Jathang section in northeastern India. Palaeogeography, Palaeoclimatology, Palaeoecology 497: 139–56.

Punekar J & Saraswati PK 2010. Age of the Vastan Lignite in context of some oldest Cenozoic fossil mammals from India. Journal of the Geological Society of India 76: 63–68.

Rage JC, Folie A, Rana RS, Singh H, Rose KD & Smith T 2008. A diverse snake fauna from the Early Eocene of Vastan Lignite Mine, Gujarat, India. Acta Palaeontologica Polonica 533: 391–403.

Rana RS, Kumar K & Singh H 2004. Vertebrate fauna from the subsurface Cambay Shale Lower Eocene, Vastan Lignite Mine, Gujarat, India. Current Science 87(2): 1726–1733.

Rao MR, Sahni A, Rana RS & Verma P 2013. Palynostratigraphy and depositional environment of Vastan Lignite Mine, Early Eocene, Gujarat, western India. Journal of Earth System Science 122: 289–307.

Rust J, Singh H, Rana RS, McCann T, Singh L, Anderson K, Sarkar N, Nascimbene PC, Stebner F, Thomas JC, Kraemer MS, Williams CJ, Engel MS, Sahni A & Grimaldi D 2010. Biogeographic and evolutionary implications of a Diverse Palaeobiota in Amber from the Early Eocene of India. Proceedings of the National Acadamy of Sciences USA 107 43: 1–6.

Sadowski EM, Beimforde C, Gube M, Rikkinen J, Singh H, Seyfullah LJ, Heinrichs J, Nascimbene PC, Reitner J & Schmidt AR 2012. The anamorphic genus Monotosporella Ascomycota from Eocene amber and from modern Agathis resin. Fungal biology 116 10: 1099–1110.

Sahni A, Saraswati PK, Rana RS, Kumar K, Singh H, Alimohammadian H, Sahni N, Rose KD, Singh L & Smith T 2006. Temporal constraints and depositional palaeoenvironments of the Vastan Lignite Sequence, Gujarat: analogy for the Cambay Shale hydrocarbon source rock. Indian Journal of Petroleum Geology 15: 1–20.

Samant B, Mohabey DM, Srivastava P & Thakre D 2014. Palynology and clay mineralogy of the Deccan volcanic associated sediments of Saurashtra, Gujarat: Age and paleoenvironments. Journal of Earth System Science 123: 219–32.

Samanta A, Bera MK, Ghosh R, Bera S, Fillet T, Pande K, Rathore SS, Rai J & Sarkar A 2013a. Do the large carbon isotopic excursions in terrestrial organic matter across Paleocene–Eocene boundary in India indicate intensification of tropical precipitation? Paleogeography, Palaeoclimatology, Palaeoecology 387: 91–203.

Samanta A, Sarkar A, Bera MK, Rai J & Rathore SS 2013b. Late Paleocene–Early Eocene carbon isotope stratigraphy from a near–terrestrial tropical section and antiquity of Indian mammals. Journal of Earth System Science 122: 163–171.

Singh A, Thakur OP & Singh BD 2012. Petrographic and depositional characteristics of Tarkeshwar Lignite deposits Cambay Basin, Gujarat. Journal of the Geological Society of India 80: 329–340.

Singh H, Samant B, Adatte T & Khozyem H 2014. Diverse palynoflora from amber and associated sediments of Tarkeshwar Lignite Mine, Surat District, Gujarat, India. Current Science 106(7): 930–932.

Singh H, Shukla A & Mehrotra RC 2016. A fossil coconut fruit from the Early Eocene of Gujarat. Journal of the Geological Society of India 87: 268–270.

Singh H, Prasad M & Wappler T 2019. An Early Eocene floral assemblage from the Cambay Shale (Tarkeshwar Lignite Mine) formation, Gujarat: palaeoclimatic and phytogeographic implications. Journal of Palaeontological Society of India 64(2): 184–226.

Singh VP, Singh BD, Mathews RP, Mendhe VA, Agnihotri P, Mishra S, Radhwani M, Dutta S, Subramanian KA, Singh A & Singh H 2021. Petrographical–geochemical characteristics and floral–faunal compositions of the Valia Lignite deposits from Cambay Basin Gujarat, western India. International Journal of Coal Geology 248: doi.org/10.1016/j.coal.2021.103866.

Ślipiński A 2007. Australian ladybird beetles (Coleoptera: Coccinellidae): their biology and classification. Canberra: Australian Biological Resources Study.

Smith T, Kumar K, Rana RS, Folie,A, Solé F, Noiret C, Steeman T, Sahni A & Rose KD 2016. New Early Eocene vertebrate assemblage from western India reveals a mixed fauna of European and Gondwana affinities. Geoscience Frontiers 7: 969–1001.

Steeman T 2020. Paleocene–Eocene dinoflagellate cysts from Africa, India, and Belgium. Universiteit Gent. Faculteit Wetenschappen.

Szawaryn K 2019. Unexpected diversity of whitefly predators in Eocene Baltic amber–new fossil Serangium species (Coleoptera: Coccinellidae). Zootaxa 4571(2): 270–276.

Sudhakar R & Basu DN 1973. A reappraisal of the Paleogene stratigraphy of southern Cambay Basin. Bulletin of Oil and Natural Gas Commission 10: 55–76.

Thakur B, Srivastava J, Uddandam P, Manoj MC & Prasad V 2015. Role of sedimentary processes and environmental factors in determining the distribution pattern of diatoms and marine/terrestrial palynomorphs in a tropical coastal wetland. Journal of Palaeontological Society of India 60: 71–84.

Williams GL, Fensome RA & MacRae RA 2017. DINOFLAJ3. American Association of Stratigraphic Palynologists, Data Series no. 2. http://dinoflaj.smu.ca/dinoflaj3.