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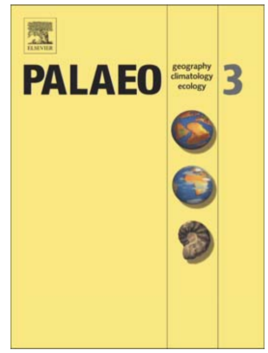

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ABSTRACT

A 105 m early Eocene section exposed in the Gurha Mine in the Nagaur-Ganganagar Basin, Rajasthan, India, archiving remains of equatorial vegetation at a time of extreme global warmth and close to the onset of the India-Eurasia collision, is investigated using palynostratigraphic and palynofacies analyses. Four palynozones e.g., *Palmidites plicatus* Singh, *Botryococcus braunii* Kützing, *Triangulorites bellus* Kar and *Ovoidites ligneoulus* are identified stratigraphically on the basis of abundance of these pollen taxa over others. The occurrence of taxonomically highly diverse angiosperm pollen in all the four palynozones attest to an extremely rich near-coastal tropical flora subject to frequent wildfires under a strongly seasonal precipitation regime. Palynotaxa characteristic of these palynozones are widely distributed in other early Paleogene sediments of India. Sedimentary organic matter (structured terrestrial, biodegraded, amorphous, grey amorphous, resins, charcoal/black-brown debris and algal remains) recovered from mire and lacustrine sediments are of terrestrial origin, recording fluctuations in burial anoxia and salinity. Episodes of elevated salinity are due either to seepage of marine waters and/or a periodic excess of evaporation over precipitation at times when the depositional system was closed.

Keywords: Palynology; Early Eocene; Palynostratigraphy; Paleoecology; Rajasthan; Lignite Mine.

1. Introduction

The early Eocene is a critical time for the evolution of the Indian flora. Palaeogeographically what is today northern peninsula India was equatorial (≤10°N), with the now subducted greater India extending towards Eurasia to the north (Molnar and Stock, 2009). Most authors consider that the Indian and Eurasian plates made contact at 55 ± 10 Ma (for a recent review of the evidence see Wang et al., 2014) and although biotic exchange between India and Eurasia undoubtedly preceeded ocean closure, the establishement of a land connection enhanced that exchange.

The early Eocene was a time of marked global warmth (e.g. Eberle and Greenwood, 2012; Zachos et al., 2001, 2003) and immediately post-dates the short-lived thermal spike known as the Paleocene-Eocene Thermal Maximum (Zachos et al., 2001), but despite its equatorial palaeoposition a recent physiognomic study of leaves preserved in the Gurha Mine, Rajasthan, showed that northwestern India experienced a climate characterised by strongly seasonal rainfall, implying a significant disruption to the 'ever wet' precipitation regime that normally exists at equatorial latitudes today. Moreover the overall temperature regime, while being megathermal, was cooler than perhaps one might have expected for a equatorial position under global 'hothouse' conditions (Shukla et al., 2014).

Given these exceptional circumstances it is important to understand better the composition of early Eocene equatorial vegetation on the Indian plate. The Gurha lignite mine, near Bikaner, in the Nagaur-Ganganagar Basin, Rajasthan (27.87398° N, 72.86709° E) provides access to a rich megaflora of early Eocene age. While the fauna has yet to be explored, insect fossils are common (Shukla et al., 2014). Here we investigate the microflora and palynofacies of the Gurha mine.

Palynostratigraphic and palynofacies analyses of the Gurha lignite mine (Fig. 1) were carried out with the aim i) to establish spore-pollen zonations in the early Eocene strata of the area, ii) to define stratigraphic ranges of significant palynotaxa, iii) to correlate the recorded palynoflora with regional and other basinal stratigraphic successions, and iv) to reconstruct palaeoenvironmental conditions prevailing during the deposition of the sediments. The study provides fundamental information on the diversity of palynofossils and their possible modern relatives in the various habitats represented in the stratigraphic succession.

Previous palynological work in the region has been limited by lack of suitable sections. Rao and Misra (1949) reported *Botrycoccus braunii* Kützing for the first time from the region, Rao and Vimal (1950, 1952) published the first palynological report from the Palana lignite, Bikaner District, and Kar and Sharma (2001) attempted a palynostratigraphic analysis of the late Paleocene-early Eocene sediments of the region. The present study is the first comprehensive work on palynoassemblages recovered from a 105 m thick sedimentary succession exposed in the Gurha lignite mine, Bikaner District, Rajasthan (Fig. 2).

Gurha today is considered to have a hot desertic climate classified as BWh by the Köppen-Geiger system. The temperature here averages 26.3 °C and the average annual rainfall is 195 mm (Kumar et al., 2003). The climate is characterised by extremes of temperature (maximum 48°C and minimum 3°C) with the common occurrence of dust storms. The vegetation is xeric and predominantly deciduous. The most common tree found in the district is *Prosopis cineraria* followed by *Tecomella undulate, Ziziphus jujube* and *Salvadora oleoides* (Lal, 1999).

2. Stratigraphic setting

The Phanerozoic geological evolution of western Rajasthan began with the formation of rift basins as the Indian plate separated from Gondwana Supercontinent during Jurassic-Cretaceous time (Norton and Scalter, 1979; Biswas, 1987). The development of Mesozoic and Tertiary basins was largely controlled by step grabens. The accumulation of Tertiary sediments in these grabens included numerous lignite seams that occur throughout western Rajasthan. Underlying the lignites are lapillae tuffs derived from volcanism. Now altered to clay these tuffs were probably sourced from silicic (andesitic and dacitic) eruptions associated with the onset of subduction of greater India beneath Eurasia. It is on this ash-covered landscape that the lignite (peat) began to accumulate and eruptions continued sporadically through the deposition of the peat.

Gurha lignite mine is situated 22 km NW of Kolayat in the Bikaner District (Figs. 1, 3) and lies in the Nagaur-Ganganagar Basin of Rajasthan. Lignite bearing successions occur in an area of 70 km long and 30 km wide associated with the early Paleogene (Paleocene-Eocene) Palana Formation in the Palana and Kolayat sub-basins (Aggarwal et al., 2011). In Gurha, a 38.5 m thick lignite seam (Fig. 2) was found at the depth of 105 m below the surface (Shukla et al., 2014).

3. Material and methods

` A total of 115 samples were collected for palynological analysis from the sedimentary succession exposed at Gurha lignite mine (Fig. 3). Standard collecting protocols were used to avoid contamination of the samples and samples were taken after removal of the outer layer of sediments exposed to air. These collected samples were chemically processed for sedimentary organic matter in dil. HCl, 40% HF and aqueous ammonia solution. For obtaining palynological assemblages, the remaining organic material was digested further in 68% HNO_3. After neutralisation the organic matter was further treated with 3–5 % aqueous KOH solution for 4 to 5 minutes and then washed in distilled water using 15 µm pore sized sieve. The washed residues were further treated with 2 to 3 drops of dil. HCl to remove coagulation which might have formed during HF, alkali and aqueous ammonia or KOH treatment. The residues containing sedimentary organic matter were smeared in polyvinyl alcohol on slides and permanently mounted on slides with canada balsam. Out of 115 samples 73 are barren, while 22 are abundant with pollen and spores. The slides of productive samples were scanned using 10x and 25x objective lenses in order to record all kinds of organic microfossils and photographed using 40x, 63x and 100x objectives of a transmission light microscope. The various types of sedimentary organic matter were categorised according to the classification of Masron and Pocock (1981), Hart (1986) and Pocock et al. (1988). Quantitative analysis of spores and pollen grains is based on 200 counts and palynofacies on 500 counts in slides made for each sample. Frequency analysis of the sedimentary organic matter was used to interpret burial processes and environmental conditions relating to each lithology. The frequency of pteridophytic spores, angiosperm pollen grains, algae (*Botryococcus braunii*, *Ovoidites ligneolus* (Potonié) Thomson and Pflug and *Locaniella triplidiscus* Yi) and sedimentary organic matter is plotted for each lithotype according to their abundance (Fig. 2). The distribution of some pollen taxa typical of the early Eocene is compared with the regional palynoflora of other stratigraphic successions previously recorded from Rajasthan, Cambay and Kutch basins.

4. Results

4.1. Recognition of palynozones

Four palynozones were recognised on the basis of quantitative analysis and dominance of palynomorphs in particular strata (Fig. 2). The studied samples were taken at ~1 m intervals through the 105 m thick section. The pollen grains exhibiting less than 1% abundance were not included in these cenozones. Their presence or absence is generally controlled by various environmental factors, distance from the source or habitat and pollen productivity. About 51 pollen types are retrieved from the assemblage and their listing is provided as online supplementary data. The details of the four palynozones and associated palynoassemblage are interpreted below:

i) *Palmidites plicatus* Cenozone

The *Palmidites plicatus* Cenozone is represented at 10 m above (between 12 m to 18 m on the measured section) the base of the lignite beds. The bottom most lignite bed contains comparatively scanty but well preserved palynofloral remains. The grains occurring in the cenozone are: *Cyathidites australis* Couper, *Dandotiaspora telonata* Sah, Kar and Singh, *Dictyophyllidites* sp., *Polypodiaceasporites* sp., *Arengapollenites ovatus* Kar, *Retimonosulcites ovatus* Kar, *Rhipites kutchensis* Venkatachala and Kar, *Lakiapollis ovatus* Sah and Kar, *Proteacites* sp., *Triangulorites bellus* Kar, along with algal spores of *Ovoidites ligneolus* (Potonié) Thomson and Pflug and *Lecaniella triplidiscus* Yi. It is important to note that spores of fern taxa (*Cyathidites australis* resembling *Cyathea* Smith and *Dandotiaspora* *telonata* of the Matoniaceae) indicate their deposition adjacent to, and possibly within, the swampy habitat represented by the lignite. Other tropical angiosperm pollen grains, especially those of palms, were also associated with these swampy elements.

ii) *Botryococcus braunii* Zone

The middle part of the section (the upper part of the lignite and the lower beds of carbonaceous shales between 18 m to 38 m) is represented by an overwhelming dominance of the colonial alga *Botryococcus braunii*. The other pollen and algal spores recorded in this zone are: *Dandotiaspora telonata*, *Palmidites plicatus* Singh, *Retimonosulcites ovatus, Lakiapollis ovatus, Retitetrabrevicolporites globatus* Kar, *Retistephanocolporites kutchensis* Saxena, *Proteacidites* sp., *Triangulorites bellus, Ovoidites ligneolus* and *Lecaniella triplidiscus.*

Botryococcus appears with great abundance in this palynoassemblage. The highest frequencies are confined to the upper part of the lignite and the lower-middle part of the carbonaceous shales. *Botryococcus* has a lower abundance in the overlying laminated clays but where the sediments are more organic (i.e. in laminated carbonaceous shales) the abundance rises. *Botryococcus* colonies exhibit low abundances in those parts of the section yielding plant megafossils. This sugests the transition between a closed swamp with little standing water to more open water caused abundant growth of this colonial alga.

iii) *Triangulorites bellus* Zone

The taxa present in this palynozone are: *Dictyophyllidites kyrtomatus* Kar and Kumar, *Polypodiaceasporites* sp., *Proxapertites operculatus* van der Hammen, *Lakiapollis ovatus, Retistephanocolporites kutchensis*, *Clavatricolpites gracilis* Guzmán, *Proteacidites* sp., *Triangulorites bellus*, Tetrad pollen type A and algal remains of *Botryococcus braunii*, *Ovoidites ligneolus* and *Lecaniella triplidiscus*.

The pollen assemblage in that part of the section consisting of laminated clays and shale between 38 and 43 m is characterised by the dominance of *Triangulorites bellus*, a grain that resembles extant pollen of the tropical family Proteaceae. Abundant and morphologically diverse proteaceous pollen recorded from the Gurha lignite mine also occurs in other early Paleogene sediments of Rajasthan, Gujarat and northeast India (Kar, 1985; Kar and Kumar, 1986; Kar and Sharma, 2001).

iv) *Botryococcus braunii- Ovoidites ligneolus* assemblage zone

The top middle to the upper part of the section (laminated clay/silt, clay and carbonaceous clay between 40 to 58 m) is represented by an overwhelming dominance of the algal species *Botryococcus braunii* and *Ovoidites ligneolus* followed by *Lecaniella triplidiscus, Triangulorites bellus, Retistephanocolpites kutchensis, Proxapertites operculatus*, *Retimonosulcites ovatus*, *Matanomadhasulcites microreticulatus* Kar, *Rhoipites kutchensis* Venkatachala and Kar, *Lakiapollis ovatus*, *Retistephanocolpites kutchensis* and *Proteacidites* sp. The return of abundant algal spores in this zone must indicate a change in lake chemistrry because there is little change in sediment type. Higher in the section, however, between 82.5 m and 98.5 m the ocurrence of cross bedded sand suggests fluvial processes as distinct from quiet lacustrine conditions and it is possible that the increase in algae may be associated with a transition to an open, more ventilated lake environment caused by an influx of fresh water.

4.2. Characteristics of some significant taxa

Angiosperm pollen grains

Palmidites

The psilate/weakly granulate/scabrate and monosulcate pollen grains of *Palmidites plicatus* (Fig. 4f) are common in the early Paleogene sediments of northeastern and northwestern India. The size of the monosulcate grain is >51 µm. They show affinity with the modern pollen grains of *Pritchardia pacifica* Seem. and H. Wendl. of the family Arecaceae (Harley and Morley, 1995), which today are commonly distributed in tropical coastal vegetation.

Quilonipollenites

Quilonipollenites ornatus Ramanujam (Fig. 4g) in having a single and large sulcus is distinct from annulosulcate genera showing affinity with the family Arecaceae. It resembles pollen of the modern calamoid palm *Eugeissona insignis* Becc. (Thanikoimoni et al.,1984).

Proxapertites

The occurrence of *Proxapertites operculatus* (Fig. 4x) in the palynoassemblage is highly significant. The species is commonly found in other early Tertiary sediments of the Indian subcontinent (Germeraad et al., 1968; Muller, 1981). The genus is considered as representating an extinct group of pantropical palms (Frederiksen, 1985).

Retimonosulcites

Retimonosulcites ovatus pollen (Fig. 4w) display microreticulate exines with a wide and large sulcus, and occur mostly in Indian early Paleogene sediments (Kar, 1985). These pollen grains resemble those of modern family Arecaceae.

Tricolpites

Tricolpites reticulates Cookson ex Couper (Fig. 5d), a cosmopolitan pollen grain, occurs in the Paleogene-Neogene sediments of various parts of the world and is very common in the early Paleogene sediments of northeast and northwest India. Zarzen (1980) and Zarzen and Dettmann (1989) assigned its botanical affinity to *Gunnera* L. of the family Gunneraceae, a perennial herb widely distributed in super humid areas with heavy rainfall in tropical and subtropical regions, although in cultivation it can survive in mild temperate climates.

Lakiapollis

Lakiapollis ovatus (Fig. 5t) is characterised by a psilate/weakly scabrate exine and tri to tetracolporate apertures and occurs abundantly in the early Paleogene sediments of northwest and northeast India, showing close affinity with the extant species *Cullenia exarillata* Robyns and *Durio* Adans. (Thanikaimonii et al., 1984) of the family Bombacaceae. Plants of this family are today distributed in Southeast Asian islands, India and other megathermal forests of the tropics (Morley, 2000).

Clavaperiporites

Clavaperiporites jacobii Ramanujam (Fig. 5r) is a rounded-spheroidal pentaporate pollen grain occurring abundantly in the Ypresian deposits of northern India. Their frequency in Thanetian deposits is lower than that of grains recorded from Ypresian sediments. Thanikaimoni et al. (1984) proposed a botanical affinity of these pollen grains with modern *Daphne oleoides* Schreb. and *Gnidia glauca* (Fresen.) Gilg of the family Thymelaeaceae, which is distributed around the Mediterranean region.

Kielmeyerapollenites spp.

Tetrad pollen grains of *Kielmeyerapollenits eocenicus* Sah and Kar (Fig. 6k, l) and *K. syncolporatus* Kar and Kumar (Fig. 6j) resemble those of modern *Kielmeyera argentea* Choisy of the Calophyllaceae (Thanikaimoni et al., 1984). The fossil pollen is very common in the Paleocene-Eocene sediments of Gujarat and Meghalaya (Sah and Kar, 1974; Kumar, 1995). At present *Kielmeyera* is distributed in low to mid elevations (775-1200 m) in tropical forests of Brazil.

Triangulorites and *Proteacidites*

Pollen grains of *Triangulorites bellus* (Fig. 5w, w1, x, x1) and *Proteacidites* sp. (Fig. 5y) are common in the early Paleogene sediments of northeast India and other parts of the world (Martin, 1995). The grains show variable morphological features, but due to their triangular shape resemble several extant pollen grains of the tropical family Proteaceae. Plants of this family are arboreal in nature and distributed in tropical and temperate zones of the Southern Hemisphere.

Strobilanthidites sp.

Strobilanthidites africanus Sah (Fig. 4l) and *Strobilanthidites* sp. (Fig. 4k) resemble the modern pollen grains of the pliestesial (living for several years and dying after flowering and fruiting) woody shrub genus *Strobilanthes* Bl. (Acanthaceae). Members of this genus occur today in shrubby layers of lowland evergreen forests of peninsular India (Rawat, 2008).

Algal remains

Botryococcus braunii

Remains of a water/brackish water colonial alga (Fig. 4a) with varied shape and size (20–100 µm), having complex tubular structures and a circular to oval body.

Lecaniella

Lecaniella triplidiscus (Fig. 4z) resembles the zygospores of modern *Debarya* (Wittrock) Transeau occurring in nonmarine sediments.

Ovoidites

Ovoidites ligneolus (Fig. 4y) is zygnemataceous spore or aplanospore of *Spirogyra* Link in C.G. Nees and other filamentous algae (van Geel and van der Hammen, 1978).

4.3. Distribution of sedimentary organic matter

Terrestrial plant fragments occur with various degrees of preservation in most of the samples collected from the lignite bearing successions. The sedimentary organic matter (SOM) embodied in various lithologies may be used to infer the depositional environment (Traverse, 1994; Tyson, 1995; Batten, 1996). The relative abundance of various types of SOM e.g., structured and biodegraded terrestrial, amorphous, grey amorphous, resins, *Botryococcus* and other fresh water algae, spore-pollen content and black/brown debris depending on their preservation state, can be used to distinguish between burial under oxic, anoxic or dysoxic conditions (Fig. 7). All *Botryococcus* algal remains, either well preserved or biodegraded exhibit good fluorescence under UV. The changes in the palynoflora throughout the studied sedimentary succession, as well as palynofacies types, are presented in Fig. 2.

Sedimentary organic matter between 0–22 m

This part of the section contains a thick lignite seam with carbonaceous shale and tuff partings overlying beds of tuff and lapillae and exhibits dominance of opaque vascular tissues followed by well structured non-opaque pieces of leaves, woods and roots, resins and lesser amount of biodegraded, amorphous matter, spores and pollen grains. The representation of opaque materials and black debris in significant quantity (> 50 %) points to a prevalence of moderately oxic conditions. Towards the top of the section between 19–22 m an increase in biodegraded terrestrial, amorphous matter and a decrease in opaque tissues/black debris is evident. The enhanced frequency of biodegraded organic matter indicates an increase in anoxic conditions during burial.

Sedimentary organic matter between 22–26 m

This part of the section exhibits a dominance (22–40%) of structured terrestrial matter. Less abundant are amorphous (20–30%), biodegraded terrestrial (5–7 %) and grey amorphous (3 to 4%) organic matter. The occurrence of grey amorphous matter indicates biodegradation of algal material in the sediments. Spores and pollen are few (< 1%), while colonies of *Botryococcus braunii* make up 2 to 3% of the assemblage. However, the black debris makes up 15–20% of the assemblage. The moderate frequency of black debris and biodegraded organic matter indicates the prevalence of dysoxic conditions during the burial of plant-derived phytoclasts.

Sedimentary organic matter between 26–46 m

This part of the section is at the top of the lignite and is characterised by poorly laminated/laminated clays and shales/silts containing stringers of tuff and lapillae and abundant amorphous, structured and biodegraded terrestrial matter. Here there are lesser amounts of charcoal/black debris and fewer still spores, pollen grains and grey amorphous matter. Resins and spore-pollen grains show a uniform distribution (2–5 %). There is a significant increase of colonies of *Botryococcus braunii* with other fresh water algae (*Lecaniella triplidiscus* and *Ovoidites ligneolus*) and abundant biodegraded organic matter. The well preserved algal remains, terrestrial phytoclasts, rich biodegraded and amorphous organic matter indicate burial in fresh water/weakly saline lacustrine conditions under anoxia.

Sedimentary organic matter between 46–67 m

The upper part of this part of the section (laminated clay, carbonaceous shale) is characterised by a moderate frequency of amorphous, biodegraded terrestrial, structured terrestrial and colonies of the *Botryococcus braunii* alga. The other types, for example resins, other fresh water algae, grey amorphous matter, spores and pollen grains are represented by just 2–5 % of the assemblage. Between 60–67 m the succession is devoid of any palynoassemblage and SOM and thus is shown with gap in representation of palynofacies data (Fig. 2).

Sedimentary organic matter between 67–70 m

The argillaceous beds of laminated clay/shale between 68–70 m contain moderately high frequencies of amorphous matter (45–50 %) with lesser amounts of opaque materials (25–30 %), structured terrestrial, biodegraded forms and resins. The ratio of biodegraded and oxidised particles of black debris and charcoal suggests prevalence of anoxic conditions during burial. Opaque microscopic woody debris and black-brown plant fragments are an important component of the palynofacies content.

5. Discussion

5.1. Age of the succession

The palynoassemblage recorded from the Gurha mine section comprises significant palynotaxa assignable to an early Eocene age. Similar palynotaxa, namely *Dandotiaspora telonata, Palmidites plicatus, Retimonosulcites ovatus, Matanomadhiasulcites microreticulatus* and *Kielmeyerapollenites eocenicus* Sah and Kar were recorded from the Akli Formation (early Eocene, Rajasthan) by Tripathi et al. (2009). Kar and Sharma (2001) reported *Dandotiaspora telonata, Proxapertites operculatus, Matanomadhiasulcites* spp., *Verrumonosulcites foveolatus* Kar and Sharma, *Retitetrabrevicolporites globatus* Kar, *Duplibaculatipollis septacolpites* Kar and Sharma and *Triangulorites bellus* Kar from the early Eocene subsurface sediments of Bikaner District. Other palynotaxa, namely *Tricolpites reticulatus* Cookson ex Couper, *Ratariacolporites plicatus* Kar, *Triangulorites (Triorites) bellus* Kar, *Botryococcus, Ovoidites* (*Psiloscizosporis*) Cookson and Dettmann and many polycolporate genera recorded from the Naredi Formation (early Eocene) of Kutch by Sah and Kar (1974); Kar and Saxena (1981) and Kar (1985) are also represented in the Gurha mine palynoassemblage. Rao and Misra (1949) reported *Botryococcus braunii* for the first time from the Palana lignite of Rajasthan and it occurs with higher frequency in the Gurha lignite. These records of similar taxa show that deposition of the Gurha lignite mine is contemporaneous to the Naredi Formation of Kutch and Akli Formation of Rajasthan.

5.2. Comparison of the palynoflora with other contemporaneous deposits

Based on the palynostratigraphic characteristics and frequency distribution four cenozones can be recognised; namely the *Palmidites plicatus* zone, the *Botryoccoccus braunii* zone, the *Trianglorites bellus* zone and *Botryococcus braunii* - *Ovoidites ligneolus* assemblage zone.

These dominant taxa, though recorded from other contemporaneous deposits of India, do not usually attain the high frequencies as recorded here. The member taxa of all the four palynozones show wide palaeogeographic distribution during the early Eocene and late Paleocene. The Gurha palynoassemblages were compared with the following stratigraphic horizons:

Rajasthan

i) Akli Formation

The occurrence of *Dandotiaspora telonata, Palmidites plicatus*, *Matanomadhiasulcites microreticulatus* and *Kielmeyerapollenites eocenicus* Kar and Kumar in the Akli Formation (Tripathi et al., 2009) shows partial similarity with the Gurha palynoassemblage.

ii) Palana Lignite

Kar and Sharma (2001) recorded *Dandotiaspora telonata*, *Proxapertites operculatus*, *Matanomadhiasulcites* microreticulatus, *Retimonosulcites ovatus*, *Verrumonosulcites foveolatus, Retitetrabrevicolporites globatus*, *Duplibaculatipollis septacolpites* Kar and Sharma and *Triangulorites bellus* from the early Eocene subsurface sediments of Bikaner District. Rao and Misra (1949) recorded *Botryococcus braunii* from the Eocene sediments of Palana and this species occurs abundantly in the Gurha lignite mine section. The occurrence of these palynotaxa in both these mining areas exhibits similarity to some extent.

Gujarat

i) Kutch Basin

Kar (1985) recorded a palynoassemblage from a number of boreholes of the Naredi Formation (early Eocene). *Lakiapollis ovatus* represented in Gurha was dominant in the Naredi Formation and its abundance formed a cenozone there. Kar and Saxena (1981) and Kar (1985) recorded *Ratariacolporites plicatus* from the Naredi Formation; but this is scantily represented in the Gurha section, while a few grains of *Triangulorites bellus* present in the Naredi Formation were abundant enough to characterise a cenozone in the Gurha lignite mine.

ii) Cambay Basin

Some pollen taxa, such as *Matanomadhiasulcites microreticulatus*, *Retimonosulcites ovatus*, *Lakiapollis ovatus*, *Clavaperiporites jacobii* Ramanujam, *Dermatobrevicolporites* *exaltus* Kar and *Retistephanocolporites* sp. are also represented in the Rajpardi lignite section (Kumar, 1996). These palynoassemblages are characterised by abundant angiosperm pollen grains of tropical families.

5.3. Palaeoenvironment

The lignite bearing successions of Rajasthan show hydrocarbon potential (Raju and Mathur, 2013; Dayal et al., 2013) and so, palynofacies and palynostratigraphical analyses for determining the depositional environments and ages of the deposits are very important. The occurrence of rich sedimentary organic matter and the oil-forming colonial alga *Botryococcus braunii,* other fresh water algae (*Lecaniella triplidiscus* and *Ovoidites ligneolus*), pollen grains of the Arecaceae and other tropical taxa indicate deposition in mire and lacustrine environments of predominantly non-marine character. A small degree of saline influence is possible, either due to proximity to the coast or by evaporation periodically exceeding precipitation. The abundance of the colonial alga, *Botryococcus braunii*, and biodegraded sedimentary organic matter in most of the beds of the section is significant. This green alga flourishes in lacustrine environments but also occurs in weakly saline brackish water (Knight et al., 1970; Grice et al., 1998; Clausing, 1999). Its abundance in parts of the Gurha section indicates massive blooms during the period of deposition. The abundant and diverse terrestrial palynoflora assignable to fresh water algae, pteridophytes and angiosperms, along with megafloral leaf remains typical of tropical vegetation of the early Eocene realm though the presence of elements like *Gunnera*, which is not exclusively tropical, indicates conditions were possibly cooler than in today's equatorial regions (Shukla et al., 2014)

The occurrence of some palm taxa, namely *Palmidites plicatus*, *Retimonosulcites ovatus*, *Arengapollenites ovatus* Kar and Bhattacharya,*Quilonipollenites ornatus* indicates the existence of nearby coastal vegetation. Many taxa such as *Clavaperiporites jacobii* (Thymeliaceae), *Triangulorites bellus* and *Proteacidites* sp. (Proteaceae), *Kielmeyerapollenites* spp. (Clusiaceae), *Compositoipollenites conicus* Sah (Asteraceae), *Ericipites* spp. (Ericaceae), *Margocolporites complexum* Ramanujam (Ceasalpiniaceae), *Incrotonipollis burdwanensis* (Baksi et al.) Jensonius and Hills, *Strobilanthidites africanus* Sah (Acanthaceae) and *Crotonipollis densus* Salard Cheboldaeff (Euphorbiaceae) indicate the existence of tropical rain forest vegetation.

The palynofacies show a gradual change in the relative abundance of structured terrestrial, biodegraded terrestrial, amorphous material, resins, charcoal/black debris, microscopic algal remains and spore-pollen suggesting oxic conditions in the basal part, to anoxic at the middle and dysoxic-oxic condition at the upper part of the section. The ubiquitous occurrence of charcoal attests to frequest wildfires, consistent with a seasonally dry climate. In the modern arid landscape of Rajasthan the upper part of the section has also been influenced by oxidation penetrating from the land surface prior to mine excavation.

After comparing the palynofloral and palynofacies data, the following two depositional regimes are recognised: i) swamps situated a short distance from the coast with a small amount of incursion of saline water and ii) fluvial flood plain deposits including lacustrine environments where saline conditions predominated from time to time due to an excess of evaporation over precipitation. A seasonal oscillation between wet and semi arid conditions is suggested by analysis of woody dicot leaf form (Shukla et al., 2014). Palynoassemblages recorded from these regimes indicate the presence of swampy habitat where ferns, coastal palms, herbaceous and arboreal angiosperms fluorished.

Appendix A. Supplementary data

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References

Aggarwal, R.K., Sharma, A., Hussain, S., 2011. Geology and mineral resources of Rajasthan. Geol. Surv. India Mis. Publ. No. 30(12), 1–130.

Batten, D.J., 1996. Palynofacies and palaeoenvironmental interpretation. In: Jansonius, J. and McGregor, D.C. (Eds.)-Palynology, principles and applications. Dallas: American Association of Stratigraphic Palynologists Foundation. 3, pp. 1011–1064.

Biswas, S.K., 1987. Regional tectonic framework, structure, and evolution of the western marginal basins of India. Tectonophysics 135, 307–327.

Clausing, A., 1999. Palaeoenvironmental significance of the green alga *Botryococcus* in the lacustrine Rotliegend (Upper Carboniferous, Lower Permian). Hist. Biol. 13, 221–234.

Dayal, A.M., Mani, D., Misra, S., Patil, D.J., 2013. Shale Gas prospective of the Cambay Basin, western India. Geohorizons January, 26–31.

Eberle, J.J., Greenwood, D.R., 2012. Life at the top of the greenhouse Eocene world—a review of the Eocene flora and vertebrate fauna from Canada's High Arctic. Geol. Soc. Am. Bull. 124, 3–23.

Frederiksen, N.O., 1985. Review of early Tertiary sporomorph ecology. Am. Assoc. Strat. Palynol., Contribution Ser.15, 1–91.

Germeraad, J.H., Hopping, C.A., Muller, J., 1968. Palynology of Tertiary sediments from tropical areas. Rev. Palaeobot. Palynol. 6, 189–348.

Grice, K., Schouten, S., Nissenbaun, A., Charrach, J., Sinnighe-Damste, S.S., 1998. A remarkable paradox: Sulfurised fresh water algal (*Botryococcus braunii*) lipids in an ancient hypersaline euxinic ecosystem. Org. Geochem. 28, 195–216.

Harley, M.M., Morley, R.J., 1995. Ultrastructural studies of some fossil and extant palm pollen, and the reconstruction of the biogeographical history of subtribes Iguanurinae and Calaminae. Rev. Palaeobot. Palynol. 85, 53–182.

Hart, G.F., 1986. Origin and classification of organic matter in clastic systems. Palynol.10, 1–23.

Kar, R.K., 1985. The fossil flora of Kachchh-IV. Tertiary palynostratigraphy. Palaeobotanist 34, 1–280.

Kar, R.K., Kumar, M., 1986. Palaeocene palynostratigraphy of Meghalaya. Pollen et Spores 28, 177–217.

Kar, R.K., Saxena, R.K., 1981. Palynological investigation of a bore core near Rataria, southern Kutch, Gujarat. Geophytol.11(2), 103–124.

Kar, R.K., Sharma, P., 2001. Palynostratigraphy of Late Palaeocene and Early Eocene sediments of Rajasthan, India. Palaeontogr. B 256, 123–157.

Knights, B.A., Brown, A.C., Conway, C., Middledi, B.S., 1970. Hydrocarbons from a green form of fresh water algae *Botryococcus braunii*. Phytochem. 9, 1317–1324.

Kumar, M., 1995. Pollen tetrads from Palaeocene sediments of Meghalaya, India: Comments on their morphology, botanical affinity and geological records. Palaeobotanist 43(1), 68–81.

Kumar, M., 1996. Palynostratigraphy and palaeoecology of Early Eocene palynoflora of Rajpardi lignite, Bharuch District, Gujarat. Palaeobotanist 43(3), 110–121.

Kumar, S., Goyal, S., Parveen, F., 2003. Ethno-medico-botany of household remedies of Kolayat tehsil in Bikaner district, Rajasthan. Indian J. Traditional Knowledge 2(4), 357–365.

Lal, G., 1999. Wastelands in Bikaner District, Rajasthan. Jodhpur: Central Arid Zone Research Institute (ICAR).

Martin, A.R.H., 1995. Palaeogene proteaceous pollen and phylogeny. Alcheringa 19, 27–40.

Masron, Th.C., Pocock, S.A.J., 1981. The classification of plant derived particulate organic matters in sedimentary rocks. In: Brooks, J. (Ed.), Organic maturation studies and fossil fuel exploration. London: Academic Press, pp. 145–175.

Molnar, P., Stock, J.M., 2009. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle, dynamics. Tectonics 28, TC3001.

Morley, R.J., 2000. Origin and Evolution of Tropical Rain Forests. Chichester: John Wiley and Sons Ltd., 362 pp.

Muller, J., 1981. Fossil pollen records of extant angiosperms. Bot. Rev. 47, 1–140.

Norton, I.O., Scalter, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. J. Geophys. Res. 84, 6803–6830.

Pocock, S.A.J., Vasanthy, G., Venkatachala, B.S., 1988. Introduction to the study of particulate organic materials and ecological perspectives. J. Palynol. 23-24, 167–188.

Raju, V.S.N., Mathur, N., 2013. Rajasthan lignite as a source of unconventional oil. Curr. Sci. 104(6), 752–759.

Rao, S.R.N., Misra, S.S., 1949. An oil bearing alga from Palana lignite, Eocene of Rajasthan. Curr. Sci. 18, 380–381.

Rao A.R., Vimal, K.P., 1950. Plant microfossils from Palana lignite, Eocene, Bikaner. Curr. Sci. 19, 82–84.

Rao A.R., Vimal, K.P., 1952. Tertiary pollen from lignites of Palana (Eocene), Bikaner. Proc. Nat. Inst. Sci. India 18(6), 595–601.

Roy, A.B., Jakhar, S.R., 2002. Geology of Rajasthan (Northwest India): Precambrian to Recent). Jodhpur: Scientific Publishers.

Rawat, G.S., 2008. Special habitats and threatened plants of India. ENVIS Bulletin: Wildlife and Protected Areas. Wildlife Inst. India Publ., Dehradun 11(1), 1–239.

Sah, S.C.D., Kar, R.K., 1974. Palynology of the Tertiary sediments of Palana, Rajasthan. Palaeobotanist 21(2), 163–188.

Shukla, A., Mehrotra, R.C., Spicer, R.A., Spicer, T.E.V., Kumar, M., 2014. Cool equatorial terrestrial temperatures and the South Asian monsoon in the early Eocene: evidence from the Gurha Mine, Rajasthan, India. Palaeogeogr., Palaeoclimatol., Palaeoecol. 412, 187–198.

Thanikaimoni, G., Caratini, C., Venkatachala, B.S., Ramanujam, C.G.K., Kar, R.K., 1984. Selected Tertiary angiosperm pollen from India and their relationships with African Tertiary pollens. Trav. Sect. Sci. Tech. 19, 1–93.

Traverse, A., 1994. Sedimentation of palynomorphs and palynodebris: an introduction. In: Traverse, A. (Ed.), Sedimentation of organic particles. Cambridge: Cambridge University Press, pp. 1–8.

Tripathi, S.K.M., Kumar, M., Srivastava, D., 2009. Palynology of Lower Palaeogene (Thanetian-Ypressian) coastal deposits from Barmer Basin (Akli Formation, Western Rajasthan, India: Palaeoenvironmental and palaeoclimatic implications . Geol. Acta 7(1, 2), 147–160.

Tyson, R.V., 1995. Sedimentary Organic Matter. Organic Facies and Palynofacies. London: Chapman and Hall, 621 pp.

Van Geel, B., van der Hammen, T., 1978. Zygnemataceae in Quaternary Colombian sediments. Rev. Palaeobot. Palaynol. 25, 377–392.

Wang, C.S., Dai, J., Zhao, X., Li, Y., Graham, S.A., He, D., Ran, B., Meng, J., 2014. Outward-growth of the Tibetan Plateau during the Cenozoic: A review. Tectonophysics 621, 1–43.

Zachos, J.C, Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.

Zachos, J.C., Wara, M.W., Bohaty, S., Delaney, M.L., Petrizzo, M.R., Brill, A., Bralower, T.J., Premoli-Silva, I., 2003. A transient rise in tropical sea surface temperature during the Paleocene–Eocene Thermal Maximum. Science 302, 1551–1554.

Zarzen, D.M., 1980. The occurrence of *Gunnera* pollen in fossil record. Biotropica 12(2), 117–123.

Zarzen, D.M., Dettmann, M.E., 1989. Taxonomic revision of *Tricolpites reticulates* Cookson ex Couper, 1953 with notes on biogeography of *Gunnera* L. Pollen et Spores 31, 97–112.

EXPLANATION OF FIGURES

(The scale bar = 20 µm, unless otherwise mentioned)

Fig. 1. Geological map showing the fossil locality (after Roy and Jakhar, 2002).

Fig. 2. Showing abundance of (I) various types of sedimentary organic matter and (II) spores, pollen grains and algal remains in the Gurha lignite mine section.

Fig. 3. Showing Gurha lignite mine.

Fig. 4. Pollen and spores from the Gurha mine section. England finder co-ordinates are given as well as slide numbers for the Birbal Sahni Institute of Palaeobotany collections where the slides are deposited.

a) Colony of *Botryococcus braunii* Kützing, slide no. BSIP 15200Q41;

b) *Dandotiaspora telonata* Sah, Kar and Singh, slide no. BSIP 15203T24;

c) *Dictyophyllidites* sp., slide no. BSIP15204N11;

d) *Polypodiaceasporites* sp., slide no. BSIP 15205;

e) *Osmundacidites* sp., slide no. BSIP 15202;

f) *Palmidites plicatus* Singh, slide no. BSIP 15198L29;

g1) *Quilonipollenites ornatus* Ramanujam, slide nos. BSIP 15209;

g2) *Longapertites hammenii* Rao and Ramanujam, slide no. 15211 P42;

h) *Lonagapertites proxopertoides* var. *Reticuloides* Gujmán, slide no. BSIP 15203;

i) *Retistephanocolporites* sp., slide no. BSIP 15209;

j) *Retitricolpites bonus* Guzmán, slide no. BSIP 15231 R22;

k) *Strobilanthidites* sp. slide no. BSIP 15232 N25;

l) *Strobilanthidites africanus* Sah, slide no. BSIP 15212 P11;

m) and p) *Tricolporopollenites* sp., slide nos. BSIP 15202, 15201 S31, 15202 M39, 15202 O15;

q) and r) *Rhoipites kutchensis* Venkatachala and Kar, slide nos. BSIP 15204 R18, 15207;

s) *Retitricolpites simplex* Guzmán, slide no. BSIP 15211 W40;

t) *Polylongicolpites retipilatus* Kar and Sharma, slide no. BSIP 15226 P28;

u) *Albertipollenites kumarii* Mandal and Rao, slide no. BSIP 15203 S42;

v) Unidentified tricolporate pollen, slide no. BSIP 15206;

w) *Retimonosulcites ovatus* Kar, slide no. BSIP 15204 M35;

x) *Proxapertites operculatus* van der Hammen, slide no. BSIP 15202;

y) *Ovoidites ligneolus* Potonié ex Krutzesch, slide no. BSIP 15213 H14;

z) *Locaniella trplidiscus* Yi, slide no. BSIP 15204G31.

Fig. 5. Pollen and spores from the Gurha mine section.

a) *Clavatricolpites gracilis* Guzmán, slide no. BSIP 15203;

b) *Retitricolporites* sp., slide no. BSIP 15197;

c) *Retisyncolporites* sp. slide no. BSIP 15203;

d) *Tricolpites reticulates* Cookson ex Couper, slide no. BSIP 15229 K25;

e) *Barringtoniapollenites retipilatus* Kar and Sharma, slide no. BSIP 15229;

f) *Tricolpopollenites* sp., slide no. BSIP 15205;

g) and m) *Sastripollenites trilobatus* Venkatachala and Kar, slide nos. BSIP 15204 Q48, 15225 U29;

h) *Incrotonipollis burdwanensis* (Baksi et al.) Jensonius and Hills, slide no. BSIP 15223 K25;

i), *Crotonipollis densus* Thanikoimoni et al., slide nos. BSIP 15214 J32;

j) *Acanthotricolpites brevispinosus* Saxena and Khare, slide no. BSIP 15215 K43;

k) and l) *Margocolporites complexum* Ramanujam, slide nos. BSIP 15226V29, 15205;

n) *Ratariacolporites plicatus* Kar, slide no. BSIP 15202;

o) *Pluricollumellatepollis pachyexinus* Kar, slide no. BSIP 15223 L22;

p) and q) *Retitribrevicolporites matanomadhensis* Kar, slide nos. BSIP15225 T29, 15206;

r) *Clavaperiporites jacobii* Ramanujam, slide no. BSIP 15227 J19;

s) *Tribrevicolporites eocenicus* Kar, slide no. BSIP 15205;

t) *Lakipollis ovatus* Sah and Kar, slide no. BSIP 15203 M28;

u) and v) *Incrotonipollis neyvelii* (Baksi et al.) Jansonius and Hills, slide nos. 15225 S26, 15206;

w), w1), x) and x1) *Triangulorites bellus* Kar, slide nos. BSIP 15202 P18, 15203;

y) *Proteacidites* sp., slide no. BSIP15202 R8.

Fig. 6. Pollen and spores from the Gurha mine section.

a) and b) *Verrumonosulcites foveolatus* Kar and Sharma, slide nos. BSIP 15202 J16, 15222 M13;

c) *Duplibaculatipollenites* sp., slide no. BSIP 15203 L31;

d) *Compositoipollenites conicus* (Sah) Venkatachala and Sharma, slide no. BSIP 15218 P44;

e) Incertae sedis, slide no. BSIP15198 U18;

f) and g) *Duplibaculatipollenites pentacolpites* Kar and Sharma, slide no. BSIP 154228 V29;

h) and i) *Duplibaculatipollenites septacolpites* Kar and Sharma, slide no. BSIP 15204 P16;

j) *Kielmeyerapollenites syncolporatus* Kar and Kumar, slide nos. BSIP 15205;

k) and l) *Kielmeyerapollenites eocenicus* Sah and Kar, slide nos. BSIP 15206, 15214 R23;

m) and r) *Adenantherites* sp., slide nos. BSIP 15198 U18, 15203 V42;

n) *Ericipites sahnii* Ramanujam, slide no. BSIP 15223 Q42;

o) *Ericipites laevigatus* Kumar, slide no. BSIP 15205;

p) and q) *Tetracolporites quadrangularis* Ramanujam, slide nos. BSIP 15208 N22, 15210 Q34;

s) and t) *Retistephanocolpites* sp., slide nos. BSIP 15202 L31, 15203 M43;

u) *Alangiopollis arcotense* Navale and Misra, slide no. BSIP 15214 O10;

v) *Retitetrabrevicolporites globatus* Kar, slide no. BSIP 15202 R33;

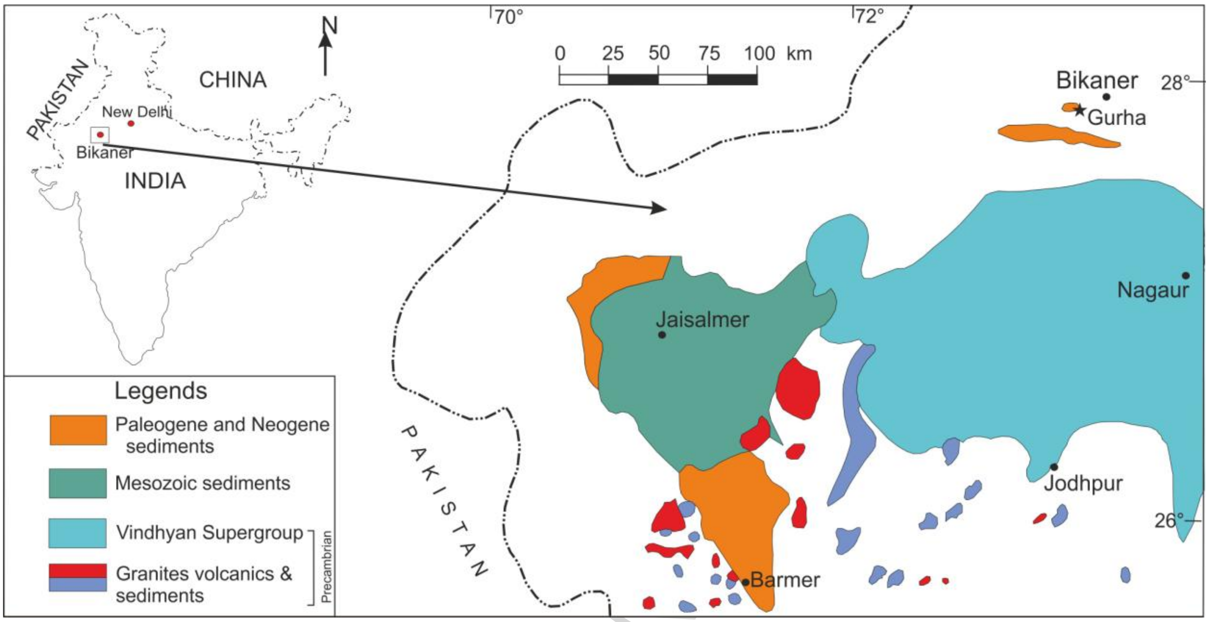
w) *Retistephanocolpites kutchensis* Saxena, slide no. BSIP 15204 H32;

x) *Polycolpites flavus* Mehrotra, slide no. BSIP 15203;

y) *Polycolpites pedaliaceoides* (Sah) Saxena, slide no. BSIP15205 L32.

Fig. 7. Palynofacies content of the Gurha mine section

a) A piece of leaf epidermal layer showing stomata and subsidiary cells, slide no. BSIP 15227 L29; b) Unaltered piece of stem showing vessels, slide no. BSIP 15230 R40; c) Partially biodegraded woody tissue, slide no. BSIP 15220; d) and i) Amorphous organic matter, slide nos. BSIP 15299, 15223 T15; e) Woody tissue with multiseriate bordered pits, slide no. BSIP 15195 K32; f) Charcoalified tissue of stem with vessels, slide no. BSIP 15194 L39; g) Biodegraded terrestrial organic matter, slide no. BSIP 15220 H 329; h) Highly altered stem tissue, slide no. BSIP 15216 O34; j) Resin globule, slide no. BSIP 15223T15; k) Ultraviolet fluorescence image of amorphous organic matter derived through biodegradation of colonial alga *Botryococcus braunii*, slide no. BSIP 15200; l) Highly biodegraded colony of *Botryococcus braunii* under UV fluorescence microscope, slide no. BSIP 15201.



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Mesozoic sediments
Vindhyan Supergroup
Granites volcanics & sediments
Precambrian

Figure 1

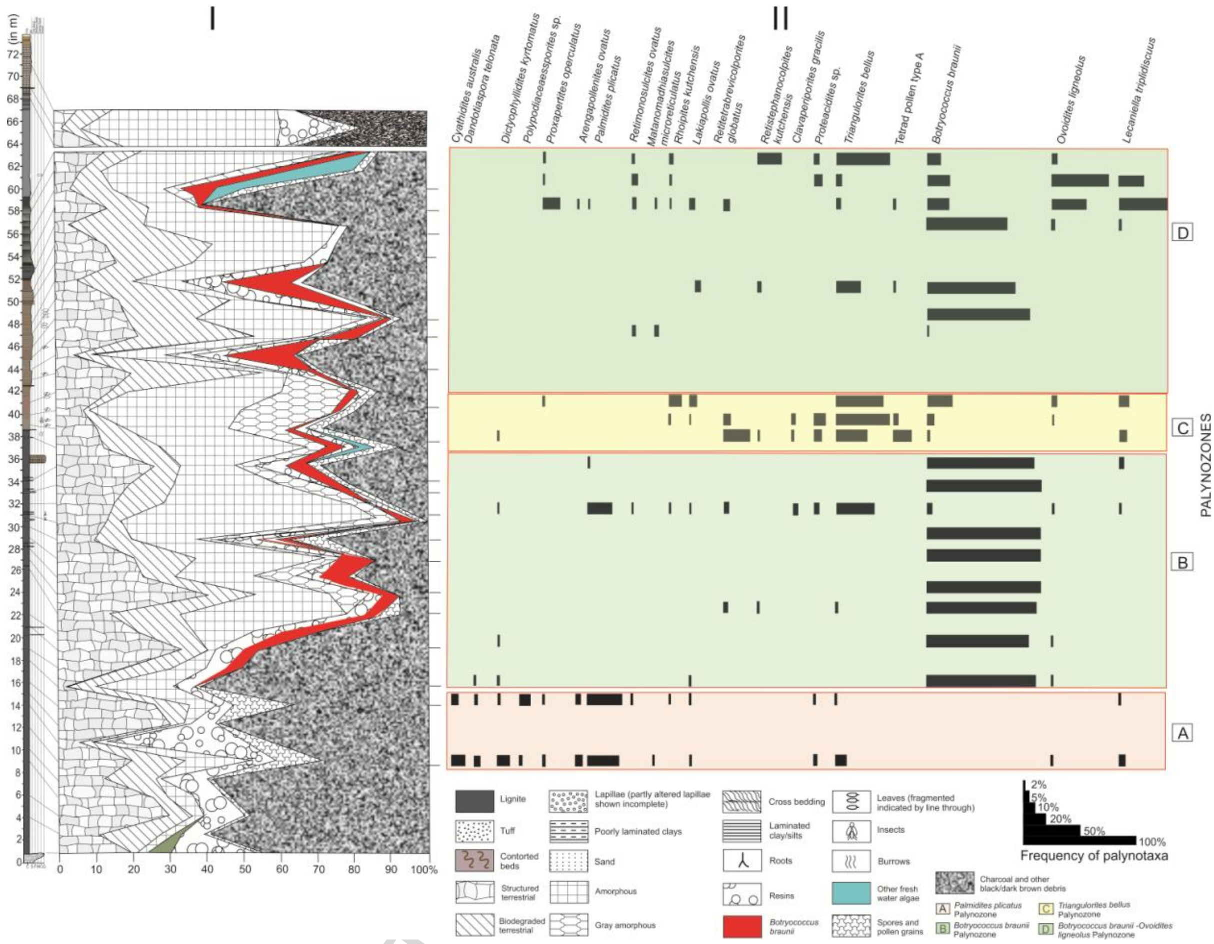

Figure 2

Figure 3

Figure 4

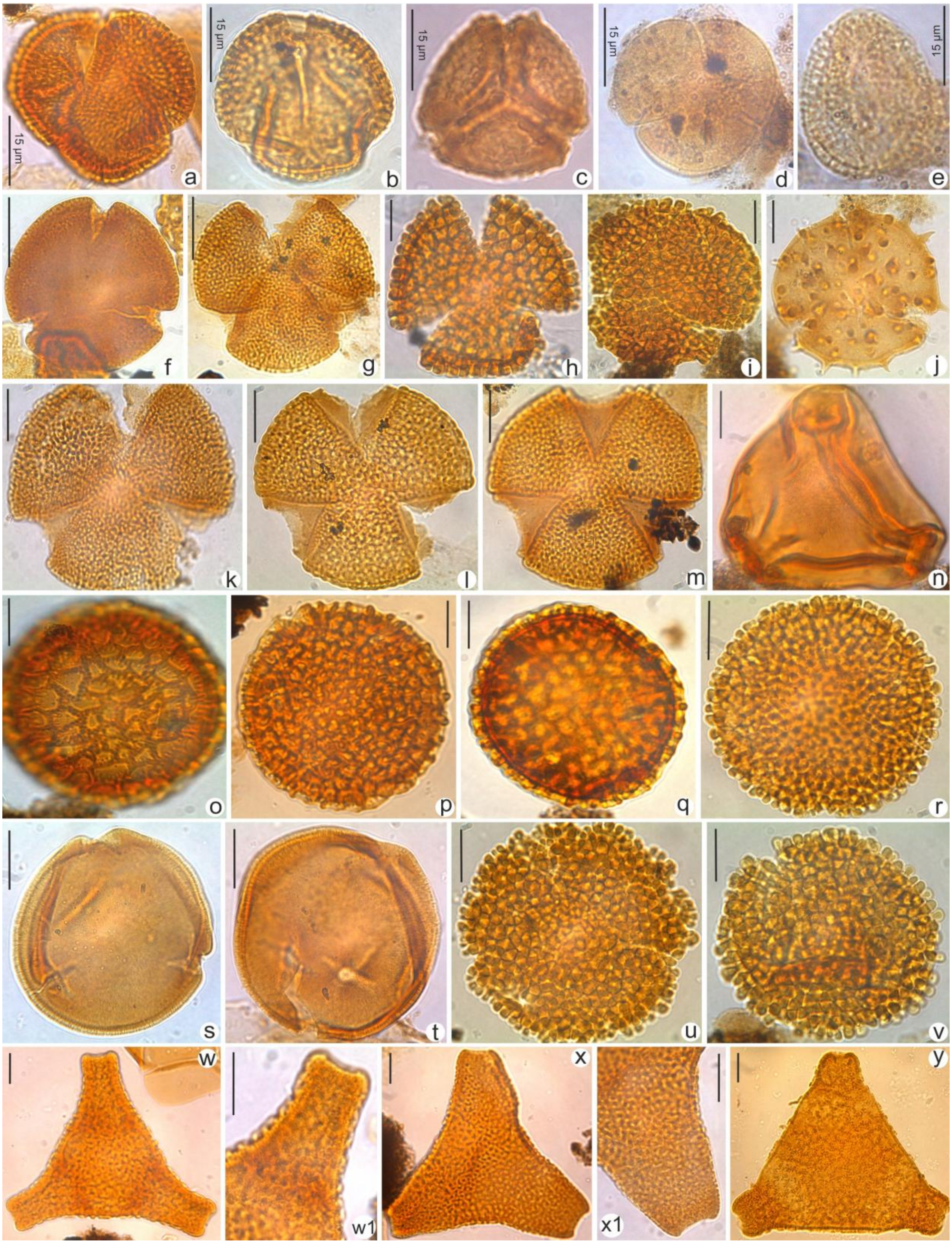

Figure 5

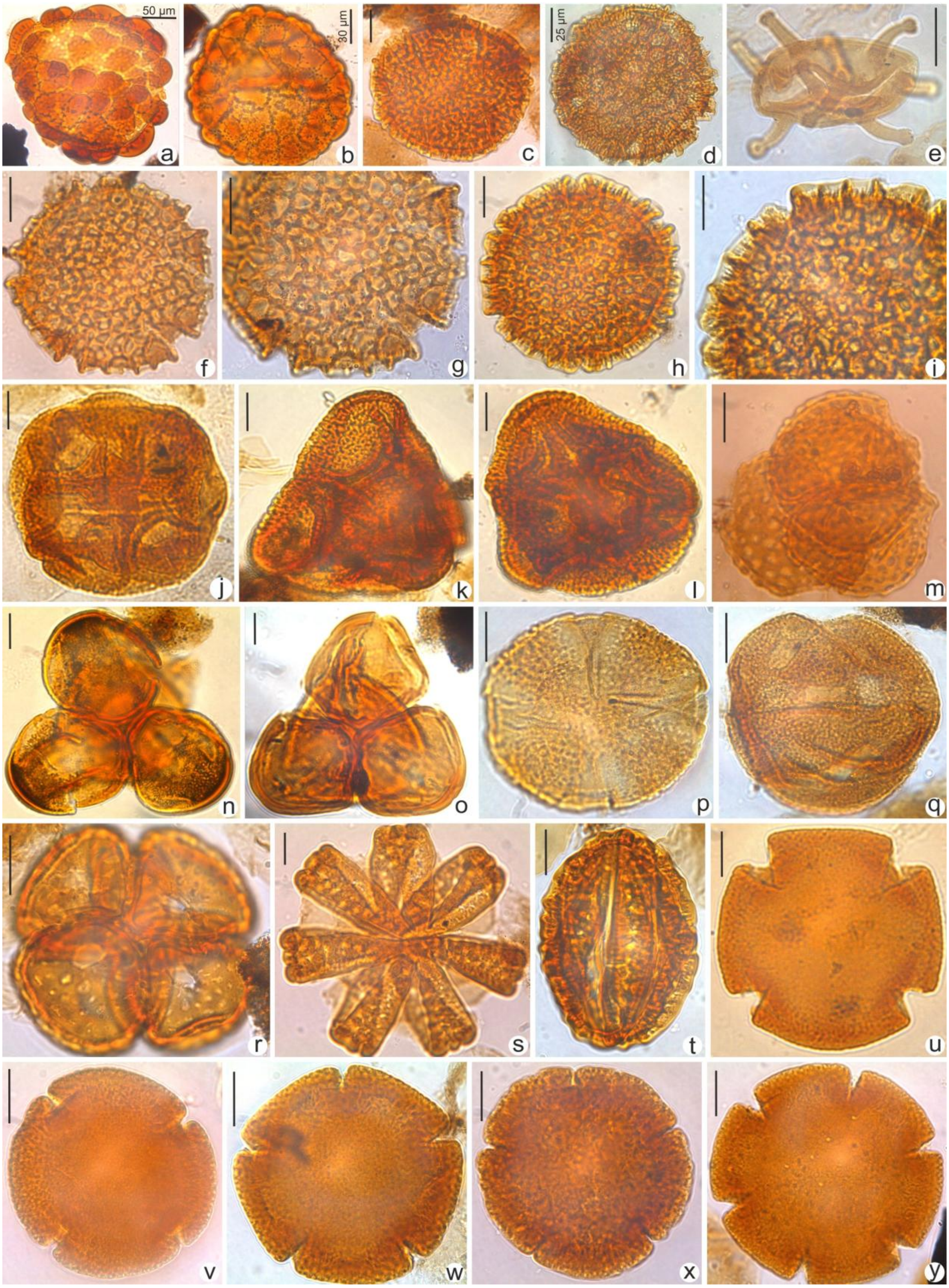

Figure 6

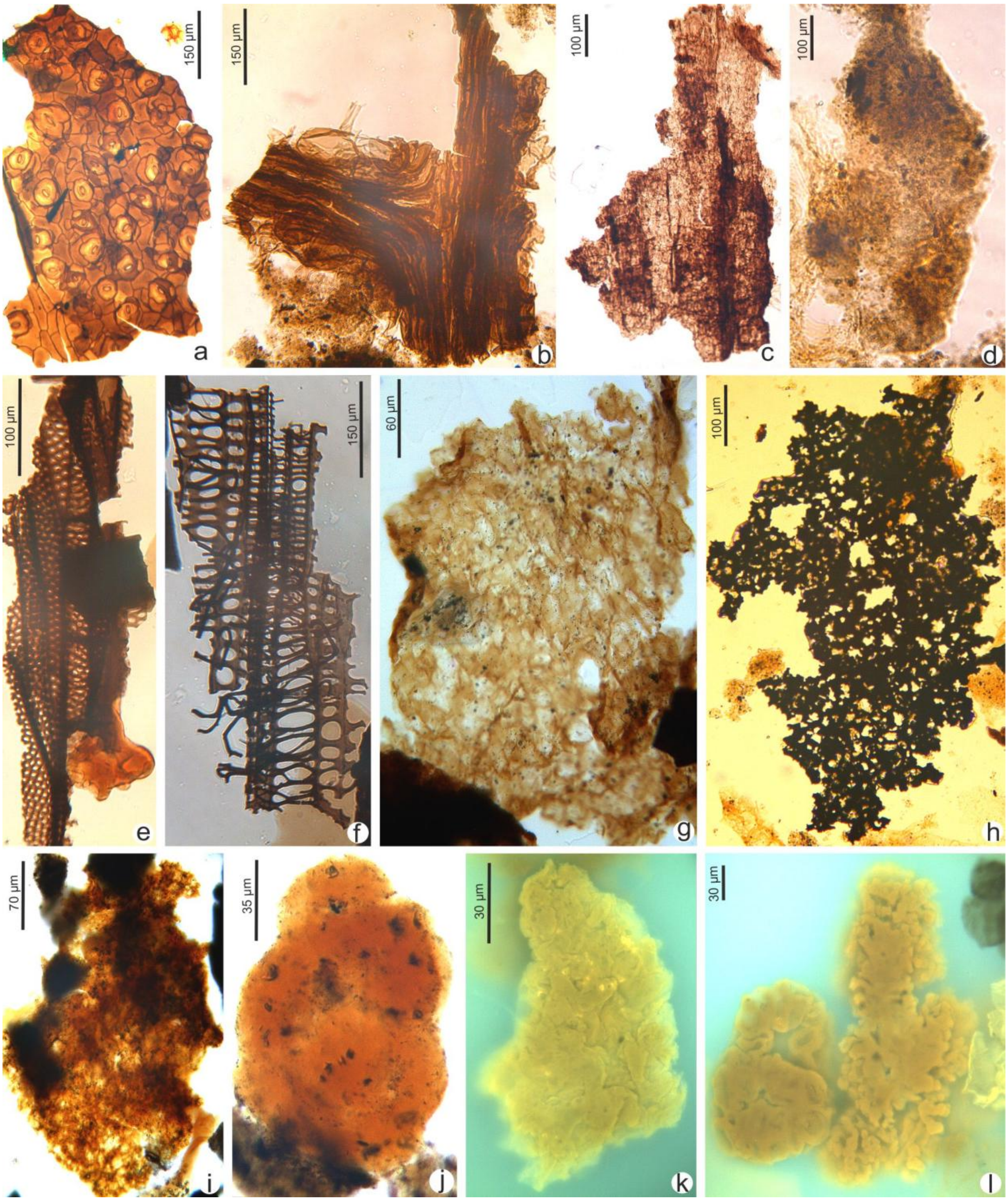
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Figure 7

Highlights

- Palynomorphs date a 105 m section in the Gurha Mine, NW India, as early Eocene.
- Four palynozones document near-coastal mire and lake margin equatorial vegetation.
- Abundant charcoal shows frequent wildfires in a strongly seasonal rainfall regime.
- Palms, ferns, Proteaceae, Gunneraceae, Bombacaceae, and algae are represented.
- Palynofacies analysis suggests fluctuating salinity and degrees of anoxia.

Keywords: Palynology, Early Eocene; Western India; Paleoecology; Lignite Mine; Biostratigraphy