Palynostratigraphy and depositional environment of Vastan Lignite Mine (Early Eocene), Gujarat, western India

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Early Eocene sedimentary successions of south Asia, are marked by the development of extensive fossil-bearing, lignite-rich sediments prior to the collision of India with Asia and provide data on contemporary equatorial faunal and vegetational assemblages. One such productive locality in western India is the Vastan Lignite Mine representing approximately a 54–52 Ma sequence dated by the presence of benthic zone marker species, *Nummulites burdigalensis burdigalensis*. The present study on Vastan Lignite Mine succession is based on the spore-pollen and dinoflagellate cyst assemblages and documents contemporary vegetational changes. 86 genera and 105 species belonging to algal remains (including dinoflagellate cysts), fungal remains, pteridophytic spores and angiospermous pollen grains have been recorded. On the basis of first appearance, acme and decline of palynotaxa, three cenozones have been recognized and broadly reflect changing palaeodepositional environments. These are in ascending stratigraphic order (i) *Proxapertites* Spp. Cenozone, (ii) *Operculodinium centrocarpum* Cenozone and (iii) *Spinizonocolpites* Spp. Cenozone. The basal sequence is lagoonal, palm-dominated and overlain by more open marine conditions with dinoflagellate cysts and at the top, mangrove elements are dominant. The succession has also provided a unique record of fish, lizards, snakes, and mammals.

1. Introduction

In recent years, Vastan Lignite Mine (latitude 21°25'47"N and longitude 73°07'30"E) in Surat, Gujarat, western India (figure 1a), has attracted attention for its rich and diverse Early Eocene floral and faunal remains that occur in the beds of Cambay Shale Formation. A diversity of spore-pollen and dinoflagellate cysts (Mandal and Guleria 2006; Garg *et al.* 2008; Tripathi and Srivastava 2012), seeds and mangrove roots (Sahni *et al.* 2006), fossil wood (Guleria *et al.* 2009) and fossil fruits (Singh *et al.* 2010) have been recorded from Vastan

Lignite Mine succession. One of the most significant findings has been the occurrence of extensive Eocene rainforests dominated by the Diptero-carpaceae as evidenced by amber chemistry and wood anatomy (Rust *et al.* 2010). Recently Dutta *et al.* (2011a) reported the occurrence of Asian depterocarps from approximately 53 Ma old sediments from western India based on fossil resin chemistry and palynological data. In addition to these, diverse herbivorous land mammals (Rana *et al.* 2005, 2008; Rose *et al.* 2009), insects preserved in amber (Alimohammadian *et al.* 2005; Rust *et al.* 2010); fossils of lower vertebrates (fish,

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Figure 1. (a) Geological map of the area around Vastan Lignite Mine, Gujarat (after Sahni *et al.* 2006). (b) Vastan Lignite Mine, Gujarat. (c) Litholog of Vastan Lignite Mine, Gujarat (after Sahni *et al.* 2006).

snakes, lizards and frogs) and invertebrates (mollusca, foraminifera and ostracoda, Rana *et al.* 2004; Sahni *et al.* 2006) have also been documented.

The south Asian Palaeogene coal measures coincide with the appearance of a diverse and new vertebrate (predominantly mammalian) faunas marking the origin of several lineages that include whales, sirenians, lagomorphs, enigmatic anthracobunids, bats, artiodactyls and anthropoid primates (Bajpai *et al.* 2005a, b, c, 2006, 2007; Rana *et al.* 2004, 2005; Rose *et al.* 2006; Sahni *et al.* 2004, 2006; Kay *et al.* 2004; Smith *et al.* 2007). Many of the mammalian lineages have close similarity to comparable taxa known from coeval sections in Europe and North America (Rose *et al.* 2009). One of the challenges is, therefore to reconstruct vegetational histories and phytogeographic distribution for low latitude floras during this time based on peat accumulation along the passive western margin of India. With this objective, a systematic palynostratigraphic study was undertaken in the Vastan Lignite Mine section, north of Surat, Cambay Basin, Gujarat, western India.

The present study deals with the spore-pollen and dinoflagellate cyst assemblages obtained from different levels of Vastan Lignite Mine and associated sediments and the data generated has been utilized in erecting broad vegetational, palynostratigraphic and palaeoecological frame work.

Mandal and Guleria (2006) for the first time recorded a rich and diverse assemblage consisting of 71 genera and 82 species of algal and fungal spores, dinoflagellate cysts, pteridophytic spores and angiosperm pollen grains from Vastan Lignite Mine section of seam I and II. The assemblage is dominated by angiospermous pollen grains and scarcity of pteridophytic spores. They have erected one new genus *Intectocolporites* and four new species, viz., *Verrutricolpites longicarpus*, *Yeguapollis indicus*, *Verrutricolporites cambayensis* and *Echitriteles communis* of angiosperm affinity. Fungal remains are represented by hyphae, microthyricaceous fruiting bodies and spores whereas algal forms are marked by *Psiloschizosporis* and *Ovoidites*. In addition to these, dinocyst (*Operculodinium centrocarpum*) and fresh water alga belonging to *Botryococcus* have also been recorded. More recently, Tripathi and Srivastava (2012) also reported pteridophytic spores (7 genera and 15 species), angiosperm pollen grains (19 genera and 34 species), fungal remains, dinoflagellate cysts (already published by Garg *et al.* 2008) and palynofacies studies from the same section. According to them, palynoflora is dominated by angiospermous pollen (48%) whereas, pteridophytic spores (25%) are sub-dominantly represented. Dinoflagellate cysts are more frequent in upper part of the sequence.

Based on the dispersed organic matter studies, they inferred that the lower and middle parts of the sequence were deposited under less anoxic conditions whereas in the upper part was deposited under the influence of completely anoxic condition.

2. Global climatic events during Palaeocene–Eocene

In the Early Eocene, the Indian plate was situated in an equatorial, high precipitation zone resulting in the formation of very thick peats preserved as lignites and coals in western and northeastern India. This was a time of several hyperthermal events (Gingerich 2006; Zachos *et al.* 2008; Clementz *et al.* 2010) which are believed to have triggered an active radiation of mammals and angiosperms including the spread of the first *Shorea* forests (Rust *et al.* 2010). During this period, Palm genera appeared, Caesalpinoideae diversified, the *Durio* (Bombacaceae) and *Alangium* became abundant, swamp forest developed and the entire continent was covered by multistoried rain forests (Morley 2000).

3. Geology and stratigraphic framework

The Cambay Basin consists of mainly fault-bounded Palaeogene and Neogene subsurface sedimentary successions. The oldest sediments range in age from the Palaeocene to Lower Eocene and constitute the Vagadkhol/Olpad and Cambay Shale formations. The Cambay Shale is confined to the deeper part of the basin and grades into the Vagadkhol Formation eastwards near the basin margins abutting the Deccan trap. The Vagadkhol Formation consists of grey mottled clay stones, gritty and conglomeratic in places with leaves and petrified wood remains (Chandra and Chowdhary 1969; Sudhakar and Basu 1973). The succeeding units in the Gulf of Cambay range in age from Middle Eocene to lower part of Upper Eocene: the Anklesvar Formation consisting of fine to medium sandstones, siltstones, greenish grey and carbonaceous shale and rare coal; the Vasco Formation having a carbonaceous shale succession with rare silt and coal, and the Kalol Formation consisting of alternating grey shales, sandstones, siltstones, silty shale with coal bands (Sudhakar and Basu 1973; Bhandari *et al.* 1991).

The Vastan lignite open cast mine is operated by Gujarat Industrial Power Corporation for thermal power. The base of the mine exposes outcrops of the Cambay Shale. There are two mineable lignite seams, one at the top as Lignite-1 and one at the mine floor referred to as Lignite-2. In addition,

there are four to five thinner seams that are up to one meter or less thick (figure 1b, c).

4. Material and methods

Samples were collected systematically from different horizons of the Vastan Lignite Mine that mainly consists of carbonaceous clay, claystone, dark coloured shales with shell layers and lignites (figure 1c). In all, 33 samples were collected and processed for the recovery of palynofossils, of which 31 samples proved to be productive. The samples were treated with HCL, HF and HNO₃ followed by a treatment of 5% KOH. The slides were prepared in polyvinyl alcohol and mounted in Canada balsam. The slides have been deposited in the museum of Birbal Sahni Institute of Palaeobotany, Lucknow with repository numbers (13583 to 13640).

5. Results and discussion

5.1 Taxonomic diversity of the Vastan Lignite Mine

The recovered palynoassemblage from the Vastan Lignite Mine succession is rich and diversified. The total assemblage consists of 86 genera and 105 species belonging to algal remains (7 genera and 7 species, including dinoflagellate cysts), fungal remains (7 genera and 8 species), pteridophytic spores (15 genera and 17 species) and angiosperm pollen (57 genera and 73 species). Qualitatively and quantitatively, the assemblage is dominated by angiosperm pollen followed by pteridophytic spores. The palynomorphs recovered from Vastan Lignite Mine have affinities with 30 extant families and are referable to Botryococcaceae, Dinophyceae, Microthyriaceae, Melaconidiaceae, Dematiaceae, Polypodiaceae, Schizaeaceae, Lycopodiaceae, Cyatheaceae, Osmundaceae, Hymenophyllaceae, Liliaceae, Arecaceae, Bombacaceae, Dipterocarpaceae, Caesalpiniaceae, Polygalaceae, Gunneraceae, Euphorbiaceae, Rhizophoraceae, Lecythidaceae, Ctenolophonaceae, Proteaceae, Thymeliaceae, Droseraceae, Lythraceae, Alangiaceae, Lamiaceae, Plumbaginaceae and Oleaceae (Appendix 1). Of these, Arecaceae is the dominant family. Palms referable to the family Arecaceae (Palmae) are woody and arborescent monocotyledons, predominantly pantropical, and restricted to evergreen and semi-evergreen forests. Photomicrographs of well preserved and stratigraphically significant taxa have been shown in plates 1, 2 and 3.

Pollen grains recovered from the lower part of the Vastan Lignite Mine Section (1A, 1 and 3 samples) have strong morphological affinities with the extant

Dipterocarpaceae pollen (plate 3(10)). The fossil pollen grains have been described under *Dipterocarpuspollenites retilpilatus* from the Miocene sediments of Kerala, south India (Kar 1992). The earliest fossil *Dipterocarpus* pollen so far recorded in SE Asia is from Oligocene (34–23 Ma) sediments of Borneo (Muller 1981). Here, we report an occurrence of *Dipterocarpus* pollen from approximately 53 Ma old sediments from Vastan Lignite Mine, western India. Our findings are corroborated by the Rust *et al.* (2010) reported well preserved insects within the fossilized resins from Vastan mine section. They also assumed that the resins were produced by dipterocarps based on presence of resin canals within the wood. Recently Dutta *et al.* (2011b) recorded pollen resembling to modern Dipterocarpaceae from the shales of Eocene lignite of Matanomadh, Kutch Basin, western India.

5.2 Quantitative analysis

For quantitative analysis of the assemblage, 200 specimens per sample were counted. However, in cases where the yield was poor, only 150 palynomorphs were counted. Percentage frequencies of each palynotaxon or group of palynotaxa were calculated. Percentage frequencies of all palynotaxa were plotted under namely, very rare (below 2%), rare (3–10%), common (11–20%), abundant (21–35%) and predominant (above 35%, figure 2). Percentage frequencies of all the palynomorphs have been critically studied and selected stratigraphically significant palynotaxa for making the biostratigraphic zonation. Three cenozones were recognized in the Vastan Lignite Mine on the basis of palynomorph frequencies. To establish and recognize these cenozones, parameters like the first appearance datum (FAD) and last appearance datum of (LAD) various palynotaxa, their maximum development, decline, restricted occurrence and absence have been taken in to consideration. Each cenozone has been formally instituted in accordance with the International Stratigraphic Guide (Hedberg 1976).

5.3 Palynostratigraphic zonation

The three cenozones established in Vastan Lignite Mine, Cambay Basin, Gujarat are given below in the ascending chronological order (figure 3).

- (i) *Proxapertites* spp. Cenozone
- (ii) *Operculodinium* centrocarpum Cenozone
- (iii) *Spinizonocolpites* spp. Cenozone

Plate 1. (1, 3) *Neocouperipollis brevispinosus* (Biswas) Venkatachala and Kar (1969), BSIP Slide Nos. 13583, T19; 13584, P27. (2) *Spinizonocolpites baculatus*, Muller (1968), BSIP Slide No. 13585, X38. (4, 5). *Acanthotricolpites bulbospinosus* Kar (1985), BSIP Slide Nos. 13586, T6; 13587, L28/3. (6–7) *Neocouperipollis kutchensis* (Venkatachala and Kar 1969) Kar and Kumar (1986), BSIP Slide No. 13588, W20/4; BSIP Slide No. 13589, G36/2. (8) *Arengapollenites ovatus* Kar and Bhattacharya (1992), BSIP Slide Nos. 13588, P10/2. (9) *Spinizonocolpites adamantus* Frederiksen (1994), BSIP Slide No. 13590, J16/4. (10) *Neocouperipollis* sp. BSIP Slide No. 13591, P8/4. (11, 12) *Proxapertites assamicus* (Sah and Dutta) Singh (1975), BSIP Slide Nos. 13584, W20/4; 13592, G28/4. (13) *Proxapertites microreticulatus* Jain *et al.* (1973), BSIP Slide No. 13593, U 25/4. (14–15) *Proxapertites operculatus* van der Hammen (1956), BSIP Slide Nos. 13586, K 28; 13594, Q 37/1. (16) *Retimonocolpites ovatus* (Sah and Kar), Kar (1985), BSIP Slide No. 13595, H 22/1. (17) *Liliacidites microreticulatus* Dutta and Sah (1970), BSIP Slide No. 13596, R 4/4. (18–19) *Retimonocolpites ellipticus* (Venkatachala and Kar) Kar (1985), BSIP Slide Nos. 13587, M 35/3; 13597, G 12. (20) *Palmidites maximus* Couper (1953), BSIP Slide No. 13584, H 6. (21) *Longapertites* sp. BSIP Slide No. 13598, K14/1. (22) *Polypodiaceasporites* sp. BSIP Slide No. 13599, F 17/1. (23) *Trichotomosulcites* sp. BSIP Slide No. 13600, T 23/2. (24) *Biretisporites* sp. BSIP Slide No. 13601, N 29. (25, 27) *Todisporites major* Couper (1953), BSIP Slide Nos. 13602, H 29; 13603, M 29/4. (26) *Pteridacidites* sp. BSIP Slide No. 13604, S 18/4. (28) *Intrapunctisporis intrapunctis* Krutzsch (1959), BSIP Slide No. 13605, O31/4. (29, 31) *Lygodiumsporites lakiensis* Sah and Kar (1969), BSIP Slide Nos. 13606, L 8/4; 13583, B 31/4. (30) *Lygodiumsporites eocaenicus* Dutta and Sah (1970), BSIP Slide No. 13585, V 36. (32) *Dandotiaspora telonata* Sah *et al.* (1971), BSIP Slide No. 13584, L 30/4. (33) *Lycopodiumsporites parvireticulatus* Sah and Dutta (1966), BSIP Slide No. 13593, J /13. (34) *Osmundacidites cephalus* Saxena (1978), BSIP Slide No. 13588, T 9/2. (35) *Lycopodiumsporites* sp. BSIP Slide No. 13599, M 14/4. Scale bar = 10 μ m.

Plate 2. (1, 5) *Spinomonosulcites achinatus* (Sah and Kar) Singh and Misra (1991), BSIP Slide Nos. 13604, G 31; 13607, E 22. (2–4) *Spinizonocolpites echinatus* Muller (1968), BSIP Slide Nos. 13599 K8/2; 13599, J 16/1. (6–7) *Retipollenites confusus* Gonzalez-Guzman (1967), BSIP Slide Nos. 13595, K 27/2; 13604, M 33/1. (8) *Ocimumpollenites indicus* Kar (1996), BSIP Slide No. 13608, W 38/2. (9) *Incrotonipollis neyvelii* (Baksi et al.) Jansonius and Hills (1981), BSIP Slide No. 13604, K 10/1. (10) *Polybrevicolporites nadhamunii* Venkatachala and Kar (1969), BSIP Slide No. 13609, V 35/2. (11) *Retistephanocolpites kutchensis* Saxena (1979), BSIP Slide No. 13610, G 6/4. (12) *Pseudonathofagidites kutchensis* Venkatachala and Kar (1969), BSIP Slide No. 13611, Q 25/3. (13, 16, 19) *Retistephanocolpites flavatus* (Sah and Kar) Saxena (1979), BSIP Slide Nos. 13599, E 13; 13588, N 16; 13612, K 37/2. (14, 17–18) *R. ornatus* (Dutta and Sah) Saxena (1982), BSIP Slide Nos. 13613, G 30/3, 13614, G 35; 13613, Q 34/4. (15, 20) *Ctenolpohonidites costatus* Hoeken-Klinkenberg (1966), BSIP Slide No. 13615, O6; 13616, H5. (21, 24) *Polysphaeridium subtile* Davey and Williams (1966), emend. Bujak et al. (1980), BSIP Slide No. 13617, U 8/4; 13618, O30. (22) *Kenleyia* sp., BSIP Slide No. 13619, L 5/1. (23) *Polysphaeridium* sp., BSIP Slide No. 13619, K 18/4. (25) *Heteraulacacysta granulata* Jan Du Chene and Adediran (1985), BSIP Slide No. 13620, W 36/1. (26–27) *Operculodinium centrocarpum* (Deflandre and Cookson) Wall (1967), BSIP Slide No. 13621, M 11; 13622, V 8/2. (28) *Spiniferites* sp., BSIP Slide No. 13623, E 6. (29) Inaperturate pollen. BSIP Slide No. 13603, S 34. (30) *Lejeunecysta hyalina* (Geroch) Kjellstrom (1972), BSIP Slide No. 13591, U 27/2. (31) Foraminiferal lining BSIP Slide No. 13624, P 21/1. (32) *Retitrescolpites robustus* (Kar and Saxena) Kar (1985), BSIP Slide No. 13625, H 10/2. (33) *Verrutricolpites* sp., BSIP Slide No. 13620, H 10/2. (34) *Matanomadhiasulcites maximus* Saxena (1980), BSIP Slide No. 13626, O15/1. (35) *Triangulorites bellus* Kar (1985), BSIP Slide No. 13620, F 36. Scale bar = 10 µm.

Plate 3. (1) *Quilonipollenites sahnii* Rao and Ramanujam (1978), BSIP Slide No. 13598, V 35. (2) *Tricolporopollis* sp., BSIP Slide No. 13627, H 40/4. (3) Tricolpate pollen, BSIP Slide No. 13599, J 31/4. (4) *Tripoporopollenites parviannulatus* Frederiksen (1994), BSIP Slide No. 13628, C 19. (5) *Droseridites* sp., BSIP Slide No. 13591, O31/4. (6) *Striacolporites cephalus* Sah and Kar (1970), BSIP Slide No. 13629, M 16/2. (7) *Lanagiopollis rugularis* Morley (1982), BSIP Slide No. 13630, G 33/2. (8) *Dermatobrevicolporites dermatus* Kar (1985), BSIP Slide No. 13630, T20. (9) *Tribrevicolporites* sp., BSIP Slide No. 13631, K 12/1. (10) *Dipterocarpuspollenites retipilatus* Kar (1992), BSIP Slide No. 13612, R 24/1. (11) *Margocolporites tsukadii* Ramanujam (1966), BSIP Slide No. 13632, V 5/3. (12, 13) *Tribrevicolporites eocaenica* Kar (1985), BSIP Slide No. 13586, G6; 13593, F 8/3. (14, 21) *Rhoipites* spp., BSIP Slide Nos. 13630, M 20; 13626, T 36/3. (15) *Paleosantalaceapites* sp., BSIP Slide No. 13633, R10/3. (16) *Dermatobrevicolporites exaltus* Kar (1985), BSIP Slide No. 13598, S 32/1. (17) *Proteacidites protrudes* Sah and Kar (1970), BSIP Slide No. 13634, G 28/2. (18) *Dorreenipites distinctus* Navale and Misra (1979), BSIP Slide No. 13635, Q 22. (19) *Retitrescolpites* sp., BSIP Slide No. 13585, R 5/2. (20, 30) *Rhoipites* spp., BSIP Slide Nos. 13636, K 22; 13637, N 32/3. (22–23) *Yeguapollis indicus* Mandal and Guleria (2006), BSIP Slide Nos. 13610, N 12/3; 13599, T 36/2. (24) *Barringtoniapollenites retipilatus* Kar and Sharma (2001), BSIP Slide No. 13625, G 36/1. (25) *Albertipollenites crassireticulatus* (Dutta and Sah) Mandal and Rao (2001), BSIP Slide No. 13584, J 15/4. (26) *Paleosantalaceapites primitiva* Biswas (1962), BSIP Slide No. 13634, D 20. (27) *Striacolporites ovatus* Sah and Kar (1970), BSIP Slide No. 13601, Q14. (28) *Paleosantalaceapites ellipticus* Sah and Kar (1970), BSIP Slide No. 13638, V13. (29) *Araliaceipollenites descretus* Venkatachala and Rawat (1973), BSIP Slide No. 13639, N 10/4. (31) *Striatopodocarpites* sp., BSIP Slide No. 13591, N 30/4. (32) *Frasnacritetrus* sp., BSIP Slide No. 13592, U 25 /4. (33) *Diporicellaesporites* sp., BSIP Slide No. 13640, N 26. (34) *Densipollenites* sp., BSIP Slide No. 13595, R 21/4. (35) *Phragmothyrites eocaenica* Edwards emend. Kar and Saxena (1976). BSIP Slide No. 13540, M 14. Scale bar = 10 μm.

Figure 3. Palynostratigraphic zonation in Vastan Lignite, Gujarat.

5.3.1 *Proxapertites* spp. Cenozoone

Type section: Lower part of the Vastan Lignite Mine exposed at 30 km northeast of Surat, Gujarat.

Lithology: This zone mainly consists of lignite alternating with claystone shell layers and shale. The thickness of the cenozoone is approximately 7 m.

Nature of contact: This cenozoone constitutes the lowest biostratigraphic unit in the section and it is overlain by the *Operculodinium centrocarpum* Cenozoone (sample nos. 1 to 11).

Species restricted to this cenozoone: *Intectocolporites baculatus* and *Retitraliporites kutchensis*

Characteristic palynofossils: *Phragmothyrites eocaenica*, *Lygodiumsporites* spp., *Intrapunctisporis intrapunctis*, *Proxapertites* spp., *Retimonosulcites*

spp., *Neocouperipollis* spp., *Lakiapollis ovatus*, *Tribrevicolporites* spp., *Lanagiopollis* spp., *Tricolporopollis* spp., *Tricolpites reticulatus*, *Retistephanocolpites* spp., *Proteacidites protrudes* and *Clavaperiporites* spp.

Remarks: The basal part of the succession exposed in Vastan Lignite Mine is a shell bed containing articulate shells, sometimes with well preserved valves lying side by side, suggesting quiet lagoonal conditions. Pyritized wood fragments and microvertebrate remains are abundant in these shell bed. During this study, a high diversity of lagoonal elements belonging to Arecaceae pollen (*Neocouperipollis* and *Proxapertites*) have been recorded, followed by mangrove elements (*Spinizonocolpites*, *Barringtoniapollenites*). In addition, terrestrial elements belonging to Bombacaceae (*Lakiapollis*, *Tricolporopollis*) and Alangiaceae (*Lanagiopollis*) are also recorded. An estuarine to lagoonal environment is inferred for the lower half of the mine section (Sahni *et al.* 2006). A thick

band of lignite (Lignite-2) is underlain by the shell band and the samples from this horizon have not yielded any spore-pollen assemblages except some cuticles and trachieds of angiosperms. The lignite is overlain by claystone with shell layers. Arecaeous pollen is predominant in these clays, followed by the main terrestrial mammal dominant horizon. Dinoflagellate cysts represented by *Polysphaeridium* are also present, but their frequency is low. Garg et al. (2008) reported the presence of *Muraetodinium fimbriatum*, *Heteraulacacysta granulata* and *Operculodinium severinii* at the base of the section.

The significant feature of this cenozoone is the predominance of Arecaeous (monocots) pollen represented by *Proxapertites*, *Neocouperipollis*, *Retimonosulcites* and *Acanthotricolpites*. Of these, the frequency of *Proxapertites* spp. is dominant and constitutes the major part of the assemblage (up to 45%), hence the cenozoone is named after it. Other important genera belong to Bombacaceae (*Lakiapollis ovatus*, *Tricolporopollis* spp.). Thymeliaceae (*Clavaperiporites* spp.) and Gunneraceae (*Tricolpites reticulatus*) are also recorded.

The basal cenozoone contains three lignite beds of varying thickness. The thickest of these several meters did not yield much pollen although it has yielded hundreds of seeds that can be clearly attributed to the family Oleaceae (Sahni et al. 2006). All three lignite seams contain fragmentary leaves, amber and an occasional carbonized wood fragment. The two upper lignite seams are thinner than the bottom seam and seem to have been deposited in wetter conditions as evidenced by the higher ratios of fungal remains and pteridophytic spores. The boundary between the basal and middle cenozoone is marked by sample 11 which displays predominance of dicot pollen (particularly *Lanagipollis*, *Ctenolophonidites* and *Clavaperiporites*) and the concomitant increase in the frequency of palm pollen suggesting the predominance of angiosperm-dominated forests.

Depositional environment of the cenozoone: The pollen spectra of this cenozoone indicate that lagoonal elements are dominant over the fresh water swamp forms followed by terrestrial elements. The frequency of dinoflagellate cysts (2%) is less. However, this cenozoone contains the main vertebrate producing layer that has diverse terrestrial mammals varying from large anthracobunids about a meter in length to small rodents with a large population of artiodactyls, primates, lagomorphs and tillodonts (Rose et al. 2009). These vertebrates appear to have been secondarily concentrated in small channels debouching into nearby lagoons.

5.3.2 *Operculodinium centrocarpum* Cenozoone

Type section: Middle part of the Vastan Lignite Mine with a thickness of about 9.6 m.

Lithology: The lithology mainly consists of shale, carbonaceous clay, calcareous clay and claystone with shell layers. In between the claystone and calcareous clay, two lignite bands are present.

Nature of contact: The upper part of the cenozoone is carbonaceous clay overlain by the *Spinizonocolpites* spp. Cenozoone (sample nos. 12 to 26).

Restricted palynofossils: *Homotryblium abbreviatum*, *Operculodinium centrocarpum*, *Heteraulacacysta granulata* and *Kenleyia* sp., and the benthic foraminifer: *Nummulites burdigalensis burdigalensis*.

Characteristic palynofossils: *Todisporites major*, *Neocouperipollis* spp., *Acanthotricolpites bulbospinosus*, *Spinizonocolpites* spp., *Tricolporopollis* spp., *Ocimumpollenites indicus*, *Retistephanocolpites* spp., *Ctenolophonidites costatus* and *Droseridites* sp.

Remarks: In this cenozoone, the dinoflagellate cysts increase in frequency in the lower part of the cenozoone and become dominant at the top with the reappearance of lagoonal elements followed by terrestrial and mangrove forms. The frequency of dinoflagellate cysts increases markedly in this cenozoone with an over 74% dominance over terrestrial palynomorphs in the molluscan shell layers that overlie the lignite band.

This cenozoone is characterized by the dominance of dinoflagellate cysts (*Homotryblium abbreviatum*, *Operculodinium centrocarpum*, *Heteraulacacysta granulata* and *Kenleyia* sp.). Of these, *Operculodinium centrocarpum* constitutes the major component (in sample no. 25, the percentage is 66%) and therefore is of importance in differentiating this cenozoone from overlying *Spinizonocolpites* spp. Cenozoone. This cenozoone includes the *Nummulites burdigalensis burdigalensis* level (SBZ 10) and the foraminifera dominant interval that mostly contains small benthic species (Sahni et al. 2006). This confirms the presence of a major transgressive event with the deepening of the basin.

Depositional environment of the cenozoone: In this cenozoone, dinoflagellate cysts are dominant throughout the middle part of the Vastan Lignite Mine and indicate a near shore to neritic bathymetry. The record of benthic foraminifera (*Cibicidoides*, *Gavelinella*, *Prabullina*, *Bulimina*,

Fursenkonia, *Cibicides* and *Storsella*), and the presence of tests with large pores (Sahni *et al.* 2006) supports this view point.

5.3.3 *Spinizonocolpites* spp. Cenozoone

Type section: Upper part of Vastan Lignite Mine with a thickness of about 11.6 m.

Lithology: The lower part of the cenozoone is made up of carbonaceous clay overlain by a lignite and followed by a silt-sized sandy level intercalated with multiple highly bioturbated hardground levels (sample nos. 27 to 31).

Restricted palynofossils: *Pteridacidites* sp., *Spinomonosulcites achinatus*, *Araliaceipollenites descretus*, *Retitrescolpites* spp. and *Dorrenipites distinctus*.

Characteristic palynofossils: *Phragmothyrites eocaenica*, *Lygodiumsporites* spp., *Retipollenites confuses*, *Retimonosulcites* spp., *Proxapertites* spp., *Paleosantalaceaepites* spp., *Spinizonocolpites* spp. and *Barringtoniapollenites retipilatus*.

Remarks: This cenozoone is characterized by the dominance of mangrove pollen belonging to *Spinizonocolpites*, *Paleosantalaceaepites*, *Spinomonosulcites achinatus* and *Barringtoniapollenites*. Of these, *Spinizonocolpites* spp. are dominant (28%), hence the cenozoone is named after it. The frequency of fresh water swamp and water edge elements (*Lygodiumsporites*, *Lycopodiumsporites*, *Todisporites*), lagoonal elements (*Proxapertites*, *Neocouperipollis*) and terrestrial elements (*Lakiapollis*, *Retistephanocolpites* and *Ctenolophondites costatus*) is decreased whereas the percentage frequency of *Retipollenites confuses* increases (up to 45%).

Depositional environment of the cenozoone: In this cenozoone the frequency of mangrove elements (*Spinizonocolpites*, *Spinomonosulcites*, *Paleosantalaceaepites* and *Barringtoniapollenites*) has increased compared to the previous zones. Deposition took place in fluctuating water depths within extensive peat filled swamps, with embayments and lagoonal. Bioturbated hard grounds suggest poor rates of sediment infilling. This type of environment is also reported for coeval horizons such as the Kadi and Kalol Formations in the north of the Cambay Basin (Bhandari *et al.* 1991), and Tarakeswar Formation comprising Rajpardi Lignite (Samant and Phadtare 1997) and nearby

Bhavnagar Lignite (Samant 2000) and Surat Lignite deposits (Samant and Tapaswi 2001).

5.4 Comparison with other Early Palaeogene palynological assemblages

Spore-pollen assemblages from the extensive lignite-rich Palaeocene and Eocene successions of western India have been known for over 50 years. A significant palynoassemblage has been recorded from Early Eocene strata exposed in Rajpardi Lignite (Kar and Bhattacharya 1992; Kumar 1996; Samant and Phadtare 1997). Palynoflora recorded from these are diverse and represented by angiosperm pollen and pteridophytic spores and indicates diverse range of tropical rain forest elements (Samant and Phadtare 1997). The palynoflora reported from Early Eocene (Naredi Formation, Kutch, Gujarat) are also rich and varied with respect to the angiosperm pollen (Venkatachala and Kar 1969; Sah and Kar 1970; Kar 1978, 1985). In addition to these, palynomorphs have also been recorded from bore-hole-samples and open cast lignite mine succession of Barmer, Rajasthan (Tripathi *et al.* 2009; Tripathi and Srivastava 2010). However, most of these studies have focused more on the vegetational diversity of the floras and their palaeoecological interpretations. The present assemblage has been compared with all the known Early Eocene assemblages of India and it reveals that it is closely comparable to Rajpardi lignite and Naredi Formation (Kutch), Gujarat, India.

6. Age of the Vastan Lignite deposit

The age diagnostic benthic foraminifera *Nummulites burdigalensis burdigalensis* which is known from the upper part of the Vastan Mine sequence (figure 1c), indicates early Cuisan (ca. 53 Ma) age (Punekar and Saraswati 2010). Dinoflagellate cysts recorded in large numbers at specific levels, suggest according to Garg *et al.* (2008) an age “not older” than Thanetian and Sparnacian (ca 54–55 Ma). Clementz *et al.* (2010) reported second Eocene Thermal Maximum (ETM2; ca. 53.7 Ma) from the middle part of the Vastan Mine section based on strontium isotopes, stable carbon isotopes, microfossil biostratigraphy, and mammal fossils. Recently Dutta *et al.* (2011b) reported the occurrence of Asian deperocarps from approximately 53 Ma sediments from western India based on fossil resin chemistry and palynological data.

The palynoflora recorded from Early Eocene horizons of India (Kar 1985; Venkatachala *et al.* 1989; Samant and Phadtare 1997; Kar and Bhattacharya 1992; Kumar 1996; Mandal and Guleria 2006;

Tripathi and Srivastava 2010, 2012) shows close resemblance to the present study.

Mandal and Guleria (2006) recorded a variety of spores-pollen from Vastan Lignite Mine section and the common genera between the two studies are: *Cyathidites*, *Lygodiumsporites*, *Schizaeoisporites*, *Polypodiisporites*, *Liliacidites*, *Matanomadhiasulcites*, *Spinomonosulcites*, *Spinizonocolpites*, *Neocouperipollis*, *Acanthotricolpites*, *Proxaperites*, *Retitritilapiporites*, *Tricolpites*, *Lakiapollis*, *Margocolporites*, *Rhoipites*, *Minutitricolporites*, *Araliaceoipollenites*, *Paleosantalaceaeipites*, *Lanagiopollis*, *Incrotonipollis*, *Striacolporites*, *Clavaperiporites*, *Polygalacidites*, *Proteacidites*, *Yeguapollis*, *Retistephanocolpites*, *Ctenolophonidites*, *Pseudonathofagidites*, *Polybrevicolporites*, *Botryococcus* and *Operculodinium*.

The genera recorded from the present study and absent in Mandal and Guleria (2006) are: *Homotryblum*, *Polysphaeridium*, *Heteraulacacysta*, *Glaphyrocysta*, *Spiniferites*, *Achomosphaera*, *Lejeunecysta*, *Trichothyrites*, *Siwalikiathyrites*, *Meliola*, *Frasnacritetrus*, *Polypodiaceasporites*, *Dandotiaspora telonata*, *Leptolepidites*, *Todisporites*, *Osmundacidites*, *Intrapunctisporis*, *Biretisporites*, *Pteridacidites*, *Clavainaperturites*, *Retimonosulcites*, *Retipollenites*, *Arengapollenites*, *Longapertites*, *Quilonipollenites*, *Dorrenipites*, *Margocolporites*, *Trichotamosulcites*, *Tribrevicolporites*, *Sastriipollenites*, *Foveotricolpites*, *Triangulorites*, *Dermatobrevicolporites*, *Periretitricolporites*, *Dipterocarpuspollenites*, *Barringtoniapollenites*, *Occimumpollenites*, *Plumbaginacipites*, *Polycolpites*, *Verrustephanocolpites* and *Tripoporipollenites* (plates 1–3).

The occurrence of *Dandotiaspora telonata*, *Retipollenites confuses*, *Retimonosulcites ovatus*, *Tricolpites reticulatus*, *Sastriipollenites trilobatus*, *Occimumpollenites indicus*, *Triangulorites bellus*, *Tricolporopollis* spp. *Dipterocarpuspollenites retipilatus*, *Dermatobrevicolporites dermatus* and *Periretitricolporites anambraensis* in the present study are indicative of Early Eocene age for the Vastan Lignite Mine and not recorded by Mandal and Guleria (2006). On the basis of dinoflagellate cysts and palynological assemblage, Cambay Basin has also been assigned as Early Eocene (Mehrotra et al. 1996, 2002; Gupta et al. 1996) in age and corroborate our view.

7. Palaeoecology and depositional environment

For palaeoecological interpretations, the assemblage has been compared with modern plant and similarities found 30 families (Appendix 1).

Epiphyllous fungi mainly, represented by Microthyriaceae, are significant for indicating humidity. The fruiting bodies of these fossil fungi are abundant in the mesophytic forests of tropical to subtropical climate and for their development, heavy rainfall is essential (Dilcher 1965; Selkrik 1975). The records of fossil epiphyllous fungi such as *Phragmothyrites*, *Trichothyrites* and *Siwalikiathyrites* are good indicators of heavy precipitation during the deposition of the lignite. Pteridophytic spores are represented by the families of Osmundaceae (*Osmundacidites*, *Todisporites*), Schizaeaceae (*Lygodiumsporites*, *Schizaeoisporites*), Polypodiaceae (*Polypodiaceasporites*, *Polypodiisporites*) and collectively indicate the prevalence of perennial water in their close vicinity, and warm and humid climate. Ferns such as members of the Cyatheaceae (*Cyathidites*), Lycopodiaceae (*Lycopodiumsporites*) and Pteridaceae (*Pteris*) are indicators of thick and tropical forest. The dominant population of the palynoflora is represented by 20 families of angiosperms. Of these, Arecaceae (Monocot) is the most abundant. Palms referable to the family Arecaceae are predominantly pantropical, and restricted to evergreen and semi-evergreen forests. The members of *Arenga* (*Arengapollenites*), *Eugeissonia* (*Quilonipollenites*) and *Borassodendran* (*Retipollenites*) together with other palm genera are good indicators of thick closed vegetation. The diversity of *Spinizonocolpites* (*Nypa*) complex in the present study appears to have been governed by the exploitation of various brackish water habitats and also by the presence of more effective competitors (Frederiksen 1994). The dominance and variety of palm pollen is sufficient for interpreting the climate as definite tropical. Pollen grains belonging to Bombacaceae (*Lakiapollis ovatus* and *Tricolporopollis matanomadhensis*) are also very abundant in this assemblage. Tropical rain forest elements belonging to the families Dipterocarpaceae (*Dipterocarpuspollenites*), Ctenolophonaceae (*Ctenolophonidites*, *Retistephanocolpites*) and Oleaceae (*Retitrescolpites*) also occur in the section. The overall assemblage indicates a warm and humid climate of a coastal zone, with a dense tropical rain forest in the vicinity of the site of deposition.

The palynoflora of Vastan Lignite Mine has been segregated into different ecological groups such as fungal, marine, terrestrial, fresh water swamp and water edge, mangrove and coastal elements (figure 4). An analysis of ecological groups represented by the Vastan Lignite Mine assemblages reveals that the coastal elements are dominant over fresh water swamp and terrestrial elements in the lower part of the section. The coastal elements (*Palmidites*, *Palmaepollenites*,

Figure 4. Representation of different ecological groups and their environment in Vastan Lignite, Gujarat.

Proxapertites and *Neocouperipollis*) are dominant throughout the section. The fresh water swamp and water edge elements are rare in the lower part and increase their frequency at the above lignite seam 2 and maintain their frequency (10–20%) from the middle to top of the section. Terrestrial elements are co-dominant along with the coastal elements and shows appreciable frequency throughout the sequence. Mangrove elements (*Spinizonocolpites*, *Paleosantalaceaepites*, *Spinomonosulcites* and *Barringtoniapollenites*) are rare to dominant in the lower and middle parts of the section and predominant in the upper part. Marine elements are very rare in the lower part but increase their frequency in the middle part and dominate (*Operculodinium centrocarpum*) at the top of the middle upper part. However, they are absent above the lignite seam 1 (figure 4). The occurrence of Araliaceae (*Araliaceoipollenites*) and Proteaceae (*Proteacidites*) probably indicate the influence of wind-blown upland flora.

As discussed, the fungal remains consist of fruiting bodies, hyphae and spores occur in plenty in organic matter rich Vastan sediments indicating activity of saprophytic fungi and these

type of substrate occur in deltaic sediments (Traverse 1988). The occurrence of dinoflagellate cysts and mangrove taxa (*Spinizonocolpites*, *Paleosantalaceaepites* and *Barringtoniapollenites*) indicate marginal marine conditions. *Operculodinium centrocarpum* suggests shallow depths in inner neritic zone and low salinity (Harland 1983; Morzadec-Kerfourn 1983). *Kenleyia* complex is most common in coastal and neritic environment (Crouch and Brinkhuis 2005). Benthic foraminifera, ostracods and marine fish (gobiids) recorded from the shale horizon (Bajpai and Kapur 2004; Bhandari *et al.* 2005) also support the view of deeper marine environments for the middle part. This marine incursion probably reflects the early Eocene transgression in the Cambay Basin (Bhandari and Raju 1991). It is concluded that the deposition of the Vastan Lignite Mine succession took place in fluctuating conditions ranging through lacustrine, swamp, marshy and deltaic environments.

Figure 5 illustrates how sea level fluctuation can give rise to major environments of deposition observed at Vastan. There are basically four major elements, ranging from the marine (foraminifera,

Figure 5. Schematic diagram of palaeovegetation zones along the passive margin of the Indian Plate during the Early Eocene.

dinoflagellate cyst-dominated), through coastal palm-dominated tracts, to deciduous and tropical rainforest components. Broadly, in a vertical succession, the Vastan sequence can be divided into three distinct depositional zones. The lower part (zone-I) mainly terrestrial fresh water as evidenced by algal elements including *Botryococcus*. The dominance of dinoflagellate cysts (*Operculodinium*, *Homotryblum*, *Heteraulacacysta*, *Polysphaeridium*, *Kenleyia*, *Glaphyrocysta*, *Achomosphaera*, *Spiniferites* and *Leujenecysta hyalina*) in the middle part (zone-II) and good representation of mangrove elements (*Nypa*, *Rhizophora* and *Barringtonia*) at the upper part of the section (zone-III) indicate an estuarine environment with a marine incursion.

8. Conclusions

1. Palynological assemblage recorded from Vastan Lignite Mine consists of algal and fungal remains, dinoflagellate cysts, pteridophytic spores and angiosperm pollen grains. Qualitative and quantitative analyses reveal that angiosperm pollen register dominance over pteridophytic spores followed by dinoflagellate cysts.
2. The lower part of the Vastan Lignite Mine succession is dominated by the Arecaceous pollen (*Neocouperipollis*, *Acanthotricolpites*, *Palmaepollenites*, *Arengapollenites*, *Proxapertites*, *Dorreenipites*, *Retipollenites* and *Quilonipollenites*); middle part of the succession is dominated by dinoflagellate cysts

(*Operculodinium centrocarpum*, *Homotryblum abbreviatum*, *Polysphaeridium subtile*, *Heteraulacacysta grannulata*, *Kenleyia* sp., *Spiniferites* sp. and *Lejeunecysta hyalina*) and the upper part of the succession is represented by mangrove pollen (*Spinizonocolpites*, *Spinomonosulcites*, *Paleosantalaceapites* and *Barringtoniapollenites*).

3. On the basis of palynological data, the Vastan Lignite Mine succession is divisible in to three cenozones, viz., i) *Proxapertites* spp. Cenozone, ii) *Operculodinium centrocarpum* Cenozone and iii) *Spinizonocolpites* spp. Cenozone.
4. Deposition of the Vastan Lignite Mine succession took place in fluctuating conditions ranging through lacustrine, swampy, marshy and deltaic environments.
5. The studied succession has been assigned as Early Eocene in age by the presence of stratigraphically important marker taxa for the Early Eocene, i.e., *Retipollenites confuses*, *Proxapertites* spp., *Neocouperipollis* spp., *Spinizonocolpites* spp., *Tricolpites reticulatus*, *Sastriipollenites trilobatus*, *Striacolporites* spp., *Triangularites bellus*, *Tricolporopollis* spp. and *Retistephanocolpites* spp. The occurrence of dinoflagellate cysts (*Operculodinium centrocarpum*, *Homotryblum abbreviatum*, *Polysphaeridium subtile*, *Heteraulacacysta grannulata*, *Kenleyia* sp.) also supports an Early Eocene age.

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Appendix 1

Algal remains

Botryococcaceae: *Botryococcus braunii*

Dinoflagellate cysts

Dinophyceae: *Operculodinium centrocarpum* (Deflandre and Cookson) Wall (1967); *Homotryblum abbreviatum* Eaton (1976); *Polysphaeridium*

subtile Davey and Williams (1966), *Polysphaeridium* sp., *Heteraulacacysta granulate* Jan Du Chene and Adediran (1985); *Kenleyia* sp.; *Glaphyrocysta* sp.; *Spiniferites* sp.; *Achomosphaera* sp.; *Lejeunecysta hyalina* (Geroch) Kjellstrom (1972).

Fungal remains

Microthyriaceae: *Phragmothyrites eocaenica* Edwards emend. Kar and Saxena (1976); *Trichothyrites setiferus* (Cookson) Saxena and Misra (1990); *Siwalikiathyrites ramanujamii* Saxena and Singh (1984).

Fungal spores

Melanconidiaceae: *Meliola* sp.

Dematiaceae: *Frasnacritetrus* sp.

Pteridophytic spores

Polypodiaceae: *Polypodiaceasporites* sp.; *Polypodiisporites repandus* Takahashi (1964).

Schizaeaceae: *Schizaeoisporites palanaensis* Sah and Kar (1974); *Lygodiumsporites lakiensis* Sah and Kar (1969); *L. eocaenicus* Dutta and Sah (1970).

Lycopodiaceae: *Lycopodiumsporites parvireticulatus* Sah and Dutta (1966).

Matoniaceae: *Dandotiasporites telonata* Sah et al. (1971); *D. plicata* Sah et al. (1971); *Garotriletes assamicus* Singh and Singh (1978).

Cyatheaceae: *Cyathidites australis* Couper (1953).

Osmundaceae: *Todisporites major* Couper (1953); *Intrapunctisporis intrapunctis* Krutzsch (1959); *Osmundacidites cephalus* Saxena (1978).

Hymenophyllaceae: *Biretisporites* spp.

Pteridaceae: *Pteridacidites* sp.

Angiosperm pollen grains

Potamogetonaceae: *Clavainaperturites clavatus* van der Hammen and Wymstra (1964).

Liliaceae: *Liliacidites microreticulatus* Dutta and Sah (1970); *Matanomadhiasulcites maximus* (Saxena), Kar (1985); *Retimonosulcites ovatus* (Sah and Kar) Kar (1985); *R. ellipticus* (Venkatachala and Kar) Kar (1985).

Arecaceae: *Retipollenites confuses* Gonzalez-Guzman (1967); *Proxapertites operculatus*, van der Hammen (1956); *P. assamicus* (Sah and Dutta) Singh (1975); *P. crassimurus* (Sah and Dutta) Singh (1975); *P. reticulatus* (Kar and Saxena) Kar (1985); *Neocouperipollis brevispinosus* (Venkatachala and Kar) Kar and Kumar (1986); *N. kutchensis*

(Venkatachala and Kar) Kar and Kumar (1986), *Neocouperipollis* sp.; *Spinomonosulcites achinatus* (Sah and Kar) Singh and Misra (1991); *Acanthotricolpites kutchensis* (Kar and Kumar) Singh and Misra (1991); *Spinizonocolpites baculatus* Muller (1968); *S. echinatus* Muller (1968); *Palmidites major* Couper (1953); *Palmaepollenites kutchensis* Venkatachala and Kar (1969); *Arengapollenites ovatus* Kar and Bhattacharya (1992); *Longapertites* sp., *Quilonipollenites sahnii* Rao and Ramanujam (1978); *Retitritilapiporites kutchensis* (Venkatachala and Kar) Singh et al. (1996) and *Dorreenipites distinctus* Navale and Misra (1979).

Bombacaceae: *Lakiapollis ovatus* Venkatachala and Kar (1969); *Tricolporopollis matanomadhensis* (Venkatachala and Kar) Tripathi and Singh (1985); *T. decoris* Dutta and Sah (1970).

Caesalpiniaceae: *Margocolporites tsukadii* Ramanujam (1966); *Periretitricolpites anambraensis* Jan Du Chene et al. (1978).

Polygalaceae: *Polygalacidites rhomboides* Kar and Bhattacharya (1992).

Gunneraceae: *Tricolpites reticulatus* Cookson (1947).

Dipterocarpaceae: *Dipterocarpuspollenites retipilatus* Kar (1992).

Euphorbiaceae: *Minutitricolpites minutus* Kar (1985).

Anacardiaceae: *Rhoipites pilatus*, *R. kutchensis* Sah and Kar (1974).

Alangiaceae: *Lanagiopollis tetracolporites* Kumar (1996); *L. ruguloverrucatus* Morley (1982); *L. rugularis* Morley (1982).

Rhizophoraceae: *Paleosantalaceaeipites ellipticus*; *P. minutus* Sah and Kar (1974).

Lecythidaceae: *Barringtoniapollenites retipilatus* Kar and Sharma (2001).

Lythraceae: *Yeguapollis indicus* Mandal and Guleria (2006).

Lamiaceae: *Occimumpollenites indicus* Kar (1996).

Plumbaginaceae: *Plumbaginacipites* sp.

Araliaceae: *Araliaceoipollenites descretus* Venkatachala and Rawat (1973).

Ctenolophonaceae: *Ctenolophonidites costatus* van Hoeken-Klinkenberg (1966), *Retistephanocolpites kutchensis* Saxena (1979), *R. flavatus* (Sah and Kar) Kar (1985), *R. ornatus* (Dutta and Sah) Saxena (1982).

Proteaceae: *Proteacidites protrudes* Sah and Kar (1970).

Thymeliaceae: *Clavaperiporites jacobii* Ramanujam (1966).

Droseraceae: *Droseridites* sp.

Unidentified: *Inapertisporites kedvesii* Elsik (1968), *Inapertisporites* sp.; *Diporicellaesporites* sp., *Foveotriteles* sp.; *Leptolepidites* sp.; *Verrumonocolpites* sp., *Albertipollenites crassireticulatus*

(Dutta and Sah) Mandal and Rao (2001); *Trichotomosulcites* sp.; *Echitricolpites communis* De Silva Pares Regali et al. (1974); *Tribrevicolporites eocenicus* Kar (1985), *Tribrevicolporites* sp., *Tricolpites* sp., *Foveotricolpites* sp.; *Verrutricolpites* sp., *Sastriipollenites trilobatus* Venkatachala and Kar (1969); *Striacolporites striatus*, *S. ovatus* Sah and Kar (1970); *Triangulorites bellus* Kar (1985); *Dermatobrevicolporites dermatus* (Sah and Kar) Kar (1985); *D. exaltus* Kar (1985); *Angulocolporites microreticulatus* Kar (1985); *Verrutricolporites cambayensis* Mandal and Guleria (2006); *Intectocolporites baculatus* Mandal and Guleria (2006); *Verrustephanocolpites* sp.; *Polycolpites* sp.; *Polybrevicolporites cephalus* Venkatachala and Kar (1969); *Pseudonothofagidites kutchensis* Venkatachala and Kar (1969) and *Tripoporipollenites parviannulatus* Frederiksen (1994).

References

- Alimohammadian H, Sahni A, Patnaik R, Rana R S and Singh H 2005 First record of an exceptionally diverse and well preserved amber-embedded biota from Lower Eocene (~52 Ma) lignites, Vastan, Gujarat; *Curr. Sci.* **89** 1328–1330.
- Bajpai S and Kapur V V 2004 Oldest known gobiids from Vastan Lignite Mine (Early Eocene), Surat District, Gujarat; *Curr. Sci.* **87** 433–435.
- Bajpai S, Kapur V V, Das D P, Tiwari B N, Sarvanan N and Sharma R 2005a Early Eocene land mammals from Vastan Lignite Mine, District Surat (Gujarat), western India; *J. Palaeontol. Soc. India* **50** 101–113.
- Bajpai S, Kapur V V, Thewissen J G M, Tiwari B N and Das D P 2005b First fossil marsupials from India: Early Eocene *Indodelphis* n. gen and *Jaegeria* n. gen. from Vastan Lignite Mine, District Surat, Gujarat; *J. Palaeontol. Soc. India* **50** 147–151.
- Bajpai S, Kapur V V, Thewissen J G M, Tiwari B N, Das D P, Sharma R and Sarvanan N 2005c Early Eocene primates from Vastan Lignite Mine, Gujarat, western India; *J. Palaeontol. Soc. India* **50** 43–54.
- Bajpai S, Kapur V V, Thewissen J G M, Das D P, Tiwari B N, Sarvanan N and Sharma R 2006 New Early Eocene cambaythere (Perissodactyla, mammalian) from Vastan Lignite Mine, District Surat (Gujarat), India and an evaluation of cambaythere relationship; *J. Palaeontol. Soc. India* **51** 101–110.
- Bajpai S, Kapur V V, Das D P and Tiwari B N 2007 New Early Eocene Primates (Mammalia) from the Vastan Lignite Mine, District Surat (Gujarat), western India; *J. Palaeontol. Soc. India* **52** 231–234.
- Bhandari A and Raju D S N 1991 Tertiary sea level changes and transgression/regression cycles in Cambay, Kutch and Rajasthan basin. A review; In: *Proceedings of the Conference on Integrated and Exploratory Research. Achievements and Perspectives* (eds) Pandey J and Banerji V, Dehradun, pp. 169–177.
- Bhandari A, Gupta P K and Juyal N P 1991 Integrated exploration research in Cambay Basin: Some aspects in Paleogene stratigraphy; In: *Proceedings of the Conference on Integrated and Exploration Research, Achievements and Perspectives* (eds) Pandey J and Banerji V, KDM

- Institute of Petroleum Exploration, Dehradun, pp. 159–167.
- Bhandari A, Singh H and Rana R S 2005 A note on occurrence of ostracodes from the Vastan Lignite Mine, Gujarat; *J. Palaeontol. Soc. India* **50** 141–146.
- Biswas B 1962 Stratigraphy of the Mahadeo, Langpar, Cherra and Tura Formations, Assam, India; *Quart. J. Geo. Minn. Metall. Soc. India* **25** 1–48.
- Bujak J P, Downie C, Eaton G L and Williams G L 1980 Dinoflagellate cysts and acritarchs from the Eocene of Southern England; *The Palaeontological Association, Special Papers on Palaeontology* **24** 1–100.
- Chandra P K and Chowdhary L R 1969 Stratigraphy of the Cambay Basin; *Bull. ONGC* **6** 37–50.
- Clementz M, Bajpai S, Ravikant V, Thewissen J G M, Saravanan N, Singh I B and Prasad V 2010 Early Eocene warming events and the timing of terrestrial faunal exchange between India and Asia; *Geology* **39** 15–18.
- Cookson I C 1947 Fossil fungi from Tertiary deposits in the southern hemisphere; *Proc. Linn. Soc. N.S.W.* **72** 207–214.
- Couper R A 1953 Upper Mesozoic and Cainozoic spores and pollen grains from New Zealand; *Bull. New Zealand Geol. Surv. Palaeontology* **22** 1–77.
- Crouch E and Brinkhuis H 2005 Environmental change across the Paleocene–Eocene transition from eastern New-Zealand: A marine palynological approach; *Marine Micropaleontol.* **56** 138–160.
- Davey R J and Williams G L 1966 The genus *Hystriochosphaeridium* and its allies in Mesozoic and cainozoic dinoflagellate cysts; *Bulletin British Museum (Natural History) Geology* **3** 1–24.
- De Silva Pares Regali P M, Uesugui I and De Silva Santos A 1974 Palinologia dos sedimentos Meso-Cenozoicas do Brail (II); *Boln. Tecn. Petrosbras* **17** 263–301.
- Dilcher D L 1965 Epiphyllous fungi from Eocene deposits in western Tennessee, USA; *Palaeontographica* **116** 1–54.
- Dutta S K and Sah S C D 1970 Palynostratigraphy of the Tertiary sedimentary formations of Assam: 5. Stratigraphy and palynology of South Shillong Plateau; *Palaeontographica* **B131** 1–72.
- Dutta S, Tripathi S K M, Mallick M, Mathews R P, Greenwood, P F, Rao M R and Summons R E 2011a Eocene out-of-India dispersal of Asian dipterocarps; *Rev. Palaeobot. Palynol.* **166** 63–68.
- Dutta S, Mathews R P, Singh B D, Tripathi S K M, Singh A, Saraswati P K, Banerjee S and Mann U 2011b Petrology, palynology and organic geochemistry of Eocene lignite of Matanomadh, Kutch Basin, western India: Implications to depositional environment and hydrocarbon source potential; *Int. J. Coal Geology* **85** 90–102.
- Eaton G L 1976 Dinoflagellate cysts from the Bracklesham beds (Eocene) of the Isle of Wight, Southern England; *Bulletin British Museum (Natural History) Geology* **26** 227–332.
- Elsik W C 1968 Palynology of a Paleocene Rockdale lignite, Milan county, Texas-1. Morphology and Taxonomy; *Pollen Spores* **10** 263–314.
- Frederiksen N O 1994 Middle and late Palaeocene angiosperm pollen from Pakistan; *Palynology* **18** 91–137.
- Garg R, Ateequzaman K, Prasad V, Tripathi S K M, Singh I B, Jauhri A K and Bajpai S 2008 Age-diagnostic dinoflagellate cysts from the lignite-bearing sediments of the Vastan Lignite Mine, Surat District, Gujarat, western India; *J. Palaeontol. Soc. India* **53** 99–105.
- Gingerich P 2006 Environment and evolution through the Paleocene–Eocene thermal maximum; *Trends in Ecology & Evolution* **21** 246–253.
- Gonzalez-Guzman A E 1967 A palynologic study on the Upper Los Cuervos and Mirador Formations (Lower and Middle Eocene), Tibú Area, Colombia; *Leiden, E. J. Brill* 68p.
- Guleria J S, Sahni A, Shukla A and Singh H A 2009 *Teredolites*, infested fossil wood from the lower Eocene sediments of Vastan Lignite Mine of Gujarat, western India; *Palaeobotanist* **58** 93–99.
- Gupta A, Kotnala S K and Poovenan A 1996 Palynostratigraphy and palaeoenvironmental analysis of subsurface Paleogene sequence of Jambusar–Dabka area, south Cambay Basin; In: *Contribution to XV Indian Colloquium on Micropalaeontology and Stratigraphy* (eds) Pandey J, Azmi R J, Bhandari A and Dave A, KDM Institute of Petroleum Exploration and Wadia Institute of Himalayan Geology, Dehradun, pp. 615–633.
- Harland R 1983 Distribution maps of recent dinoflagellate cysts in bottom sediments from the north Atlantic ocean and adjacent seas; *Palaeontology* **26** 321–387.
- Hedberg H D 1976 *International Stratigraphic Guide – A Guide to Stratigraphic Classification, Terminology and Procedure* (New York, NY: Wiley), pp. 1–200.
- Hoeken-Klinkenberg P M J 1966 Maestrichtian, Paleocene and Eocene pollen and spores from Nigeria; *Leidse Geology Meded.* **38** 37–48.
- Jain K P, Kar R K and Sah S C D 1973 A palynological assemblage from Barmer, Rajasthan; *Geophytology* **3** 150–165.
- Jan Du Chene R E, Onyike M S and Sowunmi M A 1978 Some new Eocene pollen of the Ogwashi–Asaba Formation, south-eastern Nigeria; *Revista Espanola De Micropaleontologica* **10** 285–322.
- Jan Du Chene R E and Adediran S A 1985 Late Palaeocene to Early Eocene dinoflagellate from Nigeria; *Cahiers De Micropaleontologie* **3** 1–38.
- Jansonius J and Hills L V 1981 Genera file of fossil spores; Spec. Publ. Canada, Department of Geology, pp. 1–3287.
- Kar R K 1978 Palynostratigraphy of the Naredi (Lower) and the Harudi (Middle Eocene) formations in the district of Kutch, India; *Palaeobotanist* **25** 161–178.
- Kar R K 1985 The fossil floras of Kachchh-IV. Tertiary palynostratigraphy; *Palaeobotanist* **34** 1–280.
- Kar R K 1992 Occurrence of *Dipterocarpus* type of pollen from the Miocene sediments of Kerala, south India; *J. Palynol.* **28** 79–85.
- Kar R K 1996 On the origin of *Ocimum* (Lamiaceae): A palynological approach; *Palaeobotanist* **43** 45–50.
- Kar R K and Bhattacharya M 1992 Palynology of Rajpardi lignite, Cambay Basin and Gujar Dam and Akri lignite, Kutch Basin; *Palaeobotanist* **39** 250–263.
- Kar R K and Kumar M 1986 *Neocouperipollis* – a new name for *Couperipollis* Venkatachala and Kar; *Palaeobotanist* **35** 171–174.
- Kar R K and Saxena R K 1976 Algal and fungal microfossils from Matanomadh Formation (Palaeocene), Kutch, India; *Palaeobotanist* **23** 1–15.
- Kar R K and Sharma P 2001 Palynostratigraphy of Late Palaeocene and Early Eocene sediments of Rajasthan, India; *Palaeontographica* **B256** 123–157.
- Kay R F, Schmitt D, Vinyard C J, Perry J M G, Shigehara N, Takai M and Egi N 2004 The palaeobiology of Amphipithecidae, south Asian late Eocene primates; *J. Hum. Evol.* **46** 3–25.
- Kjellstrom 1972 Archaeopyle formation in the genus *Lejeunia* emend.; *Geologiske Forningenes i Stockhloim forhand ungar* **94** 467–469.
- Krutzsch W 1959 Einige neue Formgattungen und-Arten von Sporen und Pollen aus der Mitteleuropaischen

- Oberkreide und dem Tertiär; *Palaeontographica B* **105** 125–157.
- Kumar M 1996 Palynostratigraphy and palaeoecology of Early Eocene palynofloral of Rajpardi lignite, Bharuch District, Gujarat; *Palaeobotanist* **43** 110–121.
- Mandal J and Guleria J S 2006 Palynology of Vastan Lignite (Surat District), Gujarat, its age, palaeoecology and depositional environment; *Palaeobotanist* **55** 51–66.
- Mandal J and Rao M R 2001 Taxonomic revision of tricolpate pollen from Indian Tertiary; *Palaeobotanist* **50** 341–352.
- Mehrotra N C, Nautiyal D D and Berry C M 1996 Dinocyst biostratigraphy of palynozones of the Gulf of Cambay; In: *Contribution to XV Indian Colloquium on Micropalaeontology and Stratigraphy* (eds) Pandey J, Azmi R J, Bhandari A and Dave A, KDM Institute of Petroleum Exploration and Wadia Institute of Himalayan Geology, Dehradun, pp. 683–694.
- Mehrotra N C, Venkatachala B S, Swamy S N and Kapoor P N 2002 Palynology in Hydrocarbon Exploration – The Indian Scenario. Part-I; Category-I, Basins; *Geol. Soc. India Memoir* **48** 1–162.
- Morley R J 1982 Fossil pollen attributed to *Alangium* Lamarck (Alangiaceae) from the Tertiary of Malaysia; *Rev. Palaeobot. Palynol.* **36** 65–94.
- Morley R J 2000 *Origin and Evolution of Tropical Rain Forests*; John Wiley & Sons, Ltd., pp. 1–339.
- Morzadec-Kerfourn M T 1983 In teret des kystes de dinoflagelles pour l'établissement de reconstitution Paléogéographique: exemple du Golfe de Gabes (Tunisie); *Cahiers de Micropaléontologie* **4** 15–22.
- Muller J 1968 Palynology of the Pedawan and Plateau Sandstone formations (Cretaceous–Eocene) in Sarawak, Malaysia; *Micropalaeontology* **14** 1–37.
- Muller J 1981 Fossil pollen records of extant angiosperms; *Bot. Rev.* **47** 1–142.
- Navale G K B and Misra B K 1979 Some new pollen grains from Neyveli lignite, Tamil Nadu, India; *Geophytology* **8** 226–239.
- Punekar J and Saraswati P K 2010 Age of the Vastan lignite in context of some oldest Cenozoic fossil mammals from India; *J. Geol. Soc. India* **76** 63–68.
- Ramanujam C G K 1966 Palynology of the Miocene lignite from South Arcot District, Madras, India; *Pollen. Spores* **8** 149–203.
- Rana R S, Kumar K and Singh H 2004 Vertebrate fauna from the subsurface Cambay Shale (Lower Eocene), Vastan Lignite, Gujarat India; *Curr. Sci.* **87** 1726–1733.
- Rana R S, Singh H, Sahni A, Rose K D and Saraswati P K 2005 Early Eocene chiropterans from a new mammalian assemblage (Vastan Lignite Mine, Gujarat, western peninsular margin): Oldest known bats from Asia; *J. Palaeontol. Soc. India* **50** 93–100.
- Rana R S, Kumar K, Escarguel G, Sahni A, Rose K D, Smith H and Singh L 2008 An ailuravine rodent from the lower Eocene Cambay Formation at Vastan, western India, and its palaeobiogeographic implications; *Acta Palaeontologica Polonica* **53** 1–14.
- Rao K P and Ramanujam C G K 1978 Palynology of the Neogene Quilon beds of Kerala state in south India. 1. Spores of pteridophytes and pollen of monocotyledons; *Palaeobotanist* **30** 68–100.
- Rose K D, Rana R S, Sahni A, Kumar K, Missiaen P, Singh L and Smith T 2009 Early Eocene Primates from Gujarat, India; *J. Hum. Evol.* **56** 329–438.
- Rose K D, Smith T, Rana R S, Sahni A, Singh H, Missiaen P and Folie A 2006 Early Eocene (Ypresian) continental vertebrate assemblage from India, with description of a new Anthracobunid (Mammalia, Tethytheria); *J. Verte. Paleontol.* **26** 219–225.
- Rust J, Singh H, Rana R S, McCann T, Singh U, Anderson K, Sarkar N, Nascimbene P C, Stebner F, Thomas J C, Kraemer M S, Williams C J, Engel M S, Sahni A and Grimaldi D 2010 Biogeographic and evolutionary implications of a diverse paleobiota in amber from the early Eocene of India; *Proc. Nat. Acad. Sci. USA* **107** 18,360–18,365.
- Sah S C D and Dutta S K 1966 Palynostratigraphy of the sedimentary formations of Assam-1. Stratigraphical position of the Cherra Formation; *Palaeobotanist* **15** 72–86.
- Sah S C D and Kar R K 1969 Pteridophytic spores from the Laki Series of Kutch, Gujarat, India; *J. Sen. Mem. Vol. Calcutta*, pp. 109–112.
- Sah S C D and Kar R K 1970 Palynology of the Laki sediments in Kutch-3. Pollen from the bore-holes around Jhulrai, Baranda and Panandhro; *Palaeobotanist* **18** 127–142.
- Sah S C D and Kar R K 1974 Palynology of the Tertiary sediments of Palana, Rajasthan; *Palaeobotanist* **21** 163–188.
- Sah S C D, Kar R K and Singh Y 1971 Stratigraphic range of *Dandotiaspora* Gen. nov. in the Lower Eocene sediments of India; *Geophytology* **1** 54–63.
- Sahni A, Rana R S, Loyal R S, Saraswati P K, Mathur S K, Rose K D, Tripathi S K M and Garg R 2004 Western margin Palaeocene–Lower Eocene lignites: Biostratigraphic and palaeoecological constraints; *Pro. 2nd Conf. Asso. Petro. Geol. ONGC*, pp. 1–22.
- Sahni A, Saraswati P K, Rana R S, Kumar K, Singh H, Alimohammadin H, Sahni A, Rose K D, Singh L and Smith T 2006 Temporal constraints and depositional palaeoenvironments of the Vastan Lignite Sequence, Gujarat: Analogy for the Cambay shale hydrocarbon source rock; *Indian J. Petrol. Geol.* **15** 1–20.
- Samant B 2000 Palynostratigraphy and age of the Bhavnagar lignite, Gujarat, India; *Palaeobotanist* **49**(1) 101–118.
- Samant B and Phadtare N R 1997 Stratigraphic palynoflora of the Early Eocene Rajpardi lignite, Gujarat and the lower age limit of the Tarkeswar Formation of South Cambay Basin, India; *Palaeontographica B* **245** 1–108.
- Samant B and Tapaswi P M 2001 Palynology of the Surat lignite (Early Eocene) deposits of Gujarat; *J. Palaeont. Soc.* **46** 121–132.
- Saxena R K 1978 Palynology of the Matanomadh Formation in type area, north-western Kutch, India (Part-1). Systematic description of pteridophytic spores; *Palaeobotanist* **25** 448–456.
- Saxena R K 1979 Palynology of the Matanomadh Formation in type area, northwestern Kutch, India (Part-2). Systematic description of gymnospermous and angiospermous pollen grains; *Palaeobotanist* **26** 130–143.
- Saxena R K 1980 Palynology of Matanomadh Formation in type area, north-western Kutch, India (Part-3). Discussion; *Palaeobotanist* **26** 279–296.
- Saxena R K 1982 Taxonomic study of the polycolpate pollen grains from the Indian Tertiary sediments with special reference to nomenclature; *Rev. Palaeobot. Palynol.* **37** 283–315.
- Saxena R K and Misra N K 1990 Palynological investigation of the Ratnagiri Beds of Sindhu Durg District, Maharashtra; *Palaeobotanist* **38** 263–276.
- Saxena R K and Singh H P 1984 Palynology of the Pinjor Formation (Upper Siwalik) exposed near Chandigarh, India; *Palaeobotanist* **30** 325–339.
- Selkirk D R 1975 Tertiary fossil fungi from Kiandra, New South Wales; *Proc. Linn. Soc. New South Wales* **100** 70–94.

- Singh R Y 1975 Morphological study of the *Retialites complex* from Indian Tertiaries; *Geophytology* **5** 89–104.
- Singh A and Misra B K 1991 A new spinose monosulcate genus *Spinomonosulcites* and emendation of spinose porate *Acanthotricolpites*; *Rev. Palaeobot. Palynol.* **67** 217–227.
- Singh R Y and Singh H P 1978 Morphological observations on some spores and pollen grains from the Palaeocene subsurface assemblages of Garo Hills, Meghalaya; *Palaeobotanist* **25** 475–480.
- Singh A, Misra B K and Ramanujam C G K 1996 Trilapiporate pollen from Indian Palaeogene and Neogene sequences: Evolution, migration and continental drift; *Rev. Palaeobot. Palynol.* **91** 331–352.
- Singh H, Prasad M, Kumar K, Rana R S and Singh S K 2010 Fossil fruits from Early Eocene Vastan Lignite, Gujarat, India: Taphonomic and phytogeographic implications; *Curr. Sci.* **98** 1625–1632.
- Smith T, Rana R S, Missiaen P, Rose K D, Sahni A, Singh U and Singh L 2007 High bat (*Chiroptera*) diversity in the Early Eocene of India; *Naturwissenschaften* **99** 1003–1009.
- Sudhakar R and Basu D N 1973 A reappraisal of the Palaeogene stratigraphy of southern Cambay Basin; *Bull. ONGC* **10** 55–76.
- Takahashi K 1964 Sporen und pollen der oberkretazeischen hakobouchi-Schichtengruppe, Hokkaido; *Mem. Facul. Sci. Kyushu University Series* **14** 159–271.
- Traverse A 1988 Palaeopalynology *UNWINHYMAN*, Boston, pp. 1–600.
- Tripathi S K M and Singh H P 1985 Palynology of the Jaintia Group (Palaeocene–Eocene) exposed along Jowai–Sonapur Road, Meghalaya, India. Part-I. Systematic palynology; *Geophytology* **15** 164–187.
- Tripathi S K M and Srivastava D 2010 Palynological investigation, facies analysis and palaeoenvironmental interpretations from Late Palaeocene to Early Eocene lignites and associated sediments of Barmer, western India; *Palaeobotanist* **59** 1–32.
- Tripathi S K M and Srivastava D 2012 Palynology and palynofacies of the early Palaeogene lignite bearing succession of Vastan, Cambay Basin, western India; *Acta Palaeobotanica* **52** 157–175.
- Tripathi S K M, Kumar M and Srivastava D 2009 Palynology of Lower Palaeogene (Thanetian–Ypresian) coastal deposits from the Barmer Basin (Akli Formation, Western Rajasthan, India): Palaeoenvironmental and palaeoclimatic implications; *Geologica Acta* **7** 147–160.
- van der Hammen T 1956 A palynological systematic nomenclature; *Bol. Geol. Bogota* **4** 63–101.
- van der Hammen T and Wymstra T H 1964 A palynological study of the Tertiary and Upper Cretaceous of British Guiana; *Leid. Geol. Meded.* **30** 183–241.
- van Hoeken-Klinkenberg P M J 1966 Maastrichtian, Palaeocene and Eocene pollen and spores from Nigeria; *Leid. Geol. Meded.* **38** 37–48.
- Venkatachala B S and Kar R K 1969 Palynology of the Tertiary sediments of Kutch-1-Spores and pollen from Borehole no. 14; *Palaeobotanist* **17** 157–278.
- Venkatachala B S and Rawat M S 1973 Palynology of the Tertiary sediments in the Cauvery Basin-2. Oligocene–Miocene palynoflora from the subsurface; *Palaeobotanist* **22** 238–263.
- Venkatachala B S, Caratini C and Kar R K 1989 Palaeocene–Eocene marker pollen from India and tropical Africa; *Palaeobotanist* **37(1)** 1–25.
- Wall D 1967 Fossil microplankton in deep-sea cores from the Caribbean Sea; *Paleontology* **10** 95–123.
- Zachos J C, Dickens G R and Zeebe R E 2008 An early Cenozoic perspective in green house warming and carbon-cycle dynamics; *Nature* **451** 279–283.