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Palynology and palynofacies of the early Palaeogene lignite bearing succession of Vastan, Cambay Basin, Western India

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ABSTRACT. Results of the study dealing with palynological biostratigraphy and palaeoclimatic interpretations from Early Palaeogene sequence exposed in an open-cast mine located near Vastan, Gujarat, western India are presented. During Early Palaeogene, Indian subcontinent was moving northward as an isolated landmass and crossed various latitudinal positions which resulted into peculiar flora and fauna, particularly, the elements of tropical rain forest. Exciting faunal reports published in last decade from Vastan succession prompted the authors to carry out detailed palynological and palynofacies studies on these rock sequences with an objective to understand the vegetation pattern and the environment of deposition. The rock strata under investigation are referred to as Cambay Formation and are located in extreme western part of India. The studied section is 30 m thick and is constituted by shale, clay, marls and lignite beds. Palynoflora constituted by pteridophytic spores, angiospermous pollen, dinoflagellate cysts and fungal remains have been recorded. The assemblage is dominated by angiospermous pollen, of which, those having affinity with the family Arecaceae and Bombacaceae are most abundant. Most of the palynotaxa are related to plants or families presently confined within tropical to subtropical areas. Based on the palynological assemblage, the studied sequence is divided into two palynozones. The palynological assemblage suggests that large part of the sequence is of latest Palaeocene age while the upper part is Ypresian in age. Palynofacies studies indicate that lower and middle parts of the sequence were deposited under less anoxic conditions, whereas the upper part was deposited under the influence of completely anoxic conditions.

KEYWORDS: Palynology, palynofacies, palaeoenvironment, biozonation, Early Palaeogene, Western India

INTRODUCTION

Rock strata under investigation are referred to as Cambay Formation or the Cambay Shale. The Cambay Basin, encompassing these sediments, is situated on the western margin of the Indian shield and exposes Palaeogene and younger sediments (Fig. 1). Faunal remains from Early Palaeogene sediments of Vastan have been studied extensively (Bhandari 1998, Rana et al. 2004, Alimohammadian et al. 2005, Bajpai et al. 2005a, b, Bhandari et al. 2005, Sahni et al. 2006, Kumar 2006, Nolf et al. 2006, Rust et al. 2010) but little information is available on floral remains. Mandal and Guleria (2006) described some pteridophytic spores and angiospermous pollen, Garg et al. (2008) described some age-diagnostic dinoflagellate cysts and Singh et al. (2010) reported dicotyledonous fruits. Duta et al. (2011) recorded Angiosperm pollen having affinity with Dipterocarpaceae. Present paper deals with palynological and palynofacies studies on samples from Early Palaeogene sequence exposed in Vastan open-cast lignite mine (Lat. 21°25′47″N, Long. 73°07′30″E) with objectives to understand the vegetation succession and the environment of deposition.

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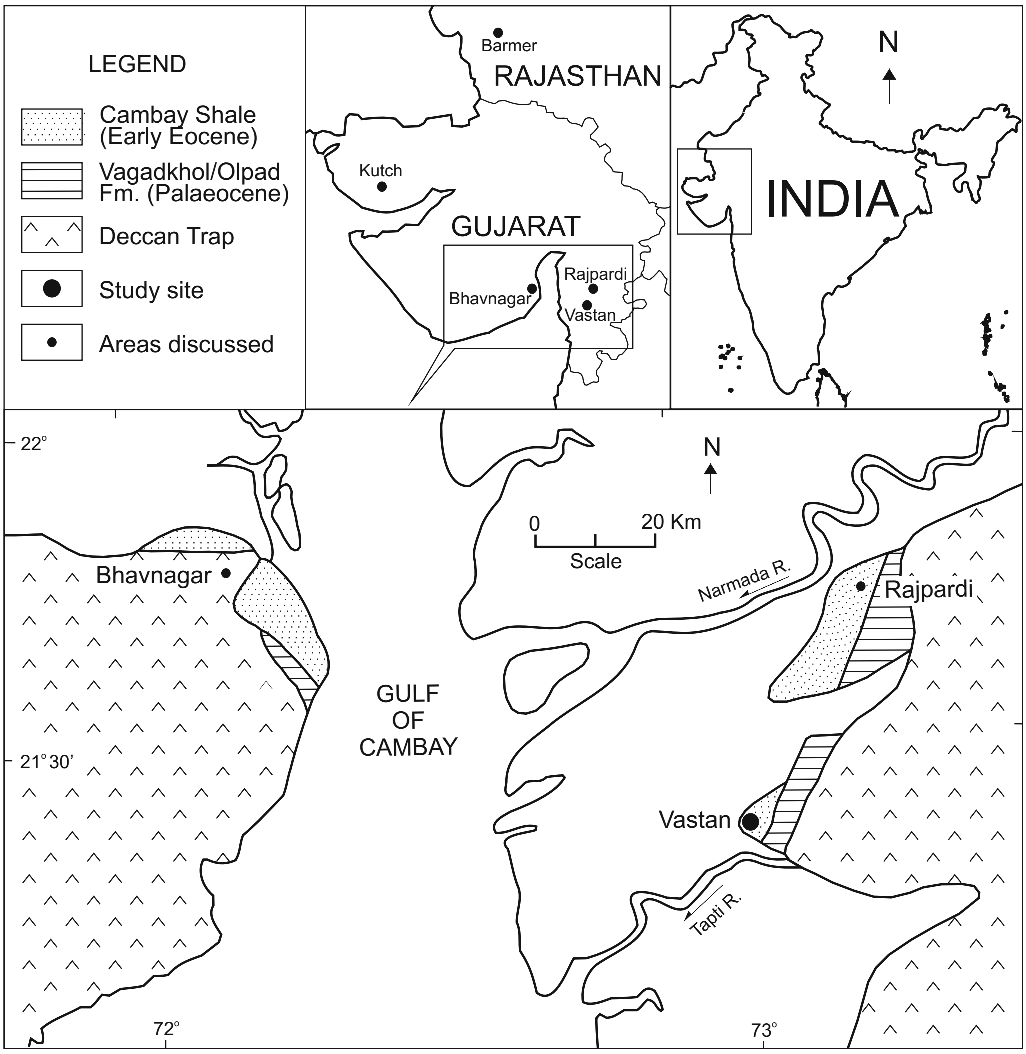

Fig. 1. Location and geological map of Vastan Lignite Mine, Gujarat, Cambay Basin, Western India

The northward drift of the Indian landmass after its separation from Gondawana land during Late Cretaceous to Early Palaeogene had profound geographic and tectonic influences. It also greatly influenced the floras and faunas (Sahni & Kumar 1974, Sahni et al. 2004, 2006, Sahni 2006, Rust et al. 2010). Workers of different disciplines studied the induced changes in flora, fauna and ecosystems due to this separation (Tripathi et al. 2000, 2003, Sahni et al. 2006, Prasad et al. 2006, 2009, Tripathi et al. 2009, Rust et al. 2010, Singh et al. 2010, Tripathi & Srivastava 2010). The Earth's atmosphere experienced global warming with Palaeocene-Eocene Thermal Maximum (PETM) followed by Early Eocene Climatic Optimum (EECO) episodes. These events incited dramatic changes in terrestrial and marine ecosystems as a result to which many organisms evolved, radiated, migrated and got extinct (Koch et al. 1992, Mehrotra et al. 2005, Sahni 2006, Prasad et al. 2006, Kent & Muttoni 2008). The Early Palaeogene floral and faunal records from Indian subcontinent are distinct in representing these climatic events and changes (Prasad et al. 2009). Being close to the African plate during Aptian time, India received diverse Late Cretaceous elements from African subcontinent and further movement of Indian plate as an isolated landmass resulted into the evolution of an independent flora (Fig. 2). Indian plate entered into moist equatorial climatic zone during Maastrichtian to Palaeocene time and at this juncture a luxuriant diversified flora with new lineages got evolved. Vegetation on Indian subcontinent underwent significant changes as it crossed varied palaeoclimatic belts during its northward journey from far southern hemisphere till its subsequent collision with tropical Asia in the northern hemisphere (Briggs 2003).

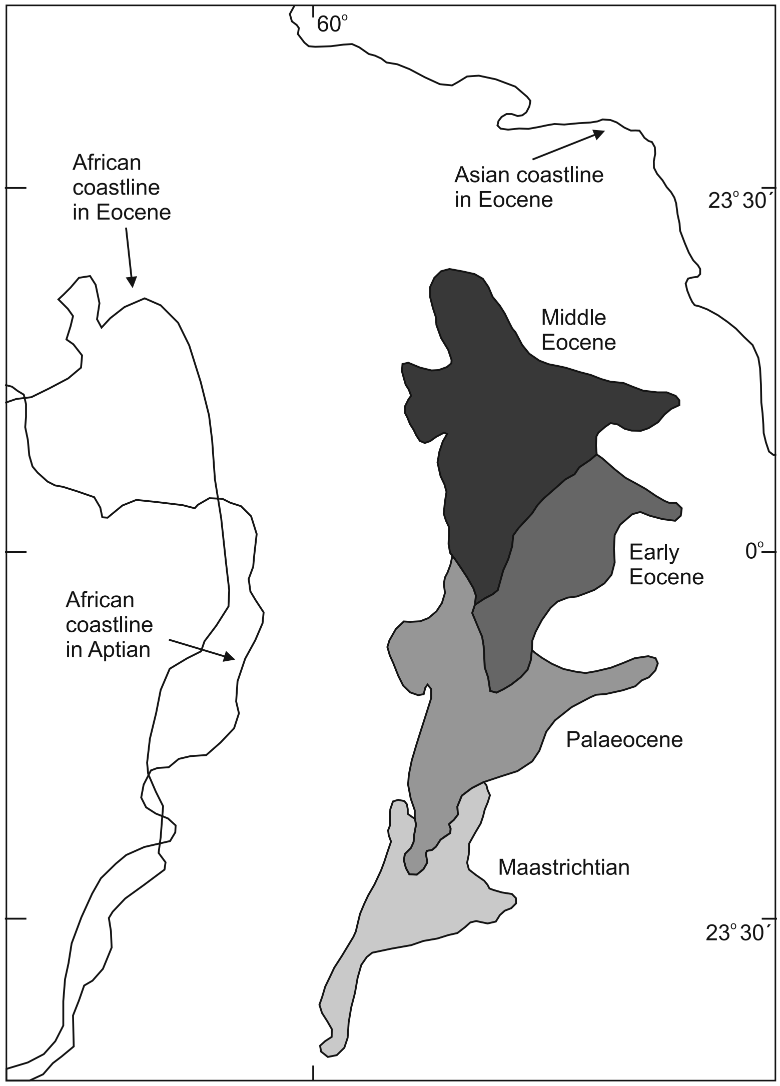

Fig. 2. Position of Indian landmass during Maastrichtian to Middle Eocene (modified after Morley 2000)

Indian Early Tertiary palynofloras provide significant information about palaeotropical floras and its biogeographical implications. The palynoflora representing this time unit is very rich and diversified reflecting climatic conditions that facilitated the proliferation of angiosperms particularly the rain forests (Morley 2000). Consequent to the movement of Indian Plate through the equator during early Eocene, extremely wet climate prevailed in western and north-eastern parts which resulted into formation of coastal lowland peats that were later converted into lignite and coal (Sahni 2006). Sequences developed along the western margin of India provide excellent opportunity to study the noticeable biotic responses during the Early Palaeogene (Sahni et al. 2006).

GEOLOGICAL SETTING

Exposures of the Cambay Shale occur as thin strips along the Saurashtra coast and to the east of the Gulf of Cambay (= Khambhat). It comprises 75–1500 m thick beds of greenish and whitish grey and black clay/shales with lignite seams. The Cambay Shale sediments overlie the sequences identified as Vagadkhol Formation which were deposited over the Deccan Volcanic Traps. The Deccan basalt and the trap-derived sediments, typical of successively older Vagadkhol Formation, are not exposed in the mine, however, these sediments are exposed in nearby localities (Sudakhar & basu, 1973). In Vastan Mine, the Cambay Shale is 20–145 m thick but the section is only about 30 m thick (Fig. 3). Two main lignite seams, one at the top (3–8 m thick) and other at the mine floor (4–6 m thick) are noticed. Besides these

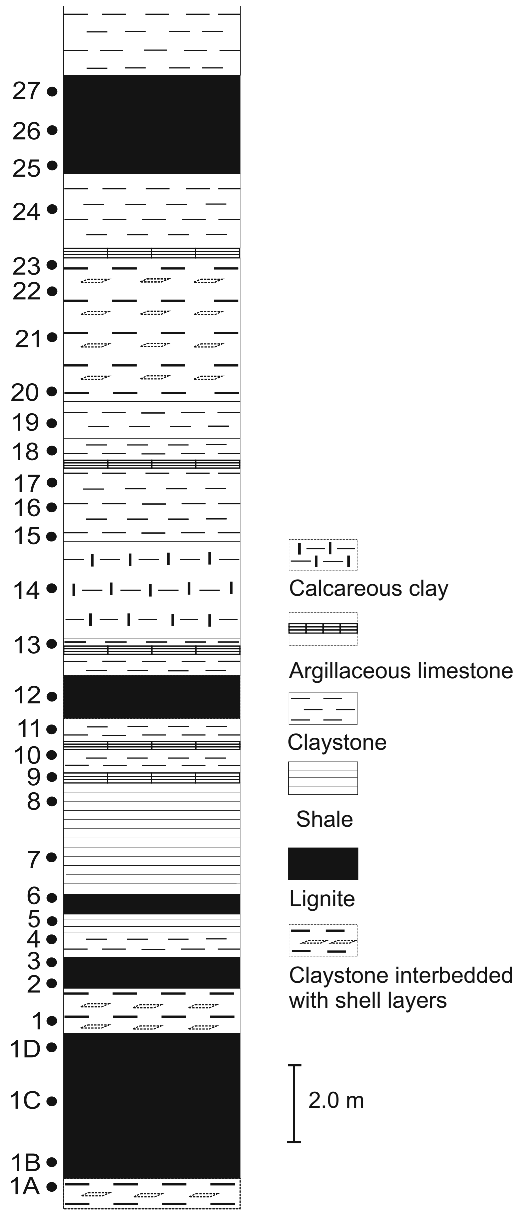

Fig. 3. Lithology of the Vastan Lignite Mine section, Cambay Basin, Western India

lignite seams, 4–5 thinner seams (up to 1 m thick) are also present. The Cambay Shale is overlain by the Upper Eocene calcareous/bentonitic variegated clay followed by sub-recent and recent alluvium comprising brown sandy clay and black cotton soil. The Vastan Lignite Mine section is made up of lignite, carbonaceous shale, claystone, calcareous clays, lensoid sandstone and argillaceous limestone. Pyrite, particularly in the form of pyritized wood fragments, is noticed throughout the sequence. The lowermost beds exposed in the mine section are represented by claystone with shell layers. Considering the features associated with shell beds, the occurrence of pyritized wood fragments and microvertebrate remains, Sahni et al. (2006) inferred an estuarine to lagoonal environment of deposition for the lower half of the Vastan mine section. The upper half of the section is characterized by the presence of foraminiferal assemblages which indicate shallow marine environment. Morphological features of the assemblage suggest that these are low-oxygen tolerant species and indicate a highly stressed shallow water environment (Sahni et al. 2006). Lower part of the foraminifera bearing interval is interpreted to have been deposited in relatively high energy conditions. A thin layer of shales within the above assemblage of smaller benthic foraminifera contains abundance of well-preserved *Nummulites*. This represents the deepest bathymetry within the exposed mine section and water depth is estimated to be about 30 metres. The *Nummulites burdigalensis* horizon is overlain by the non–marine ostracode assemblage (Bhandari et al. 1991, Bhandari 1998, 2003). In Vastan mine, this horizon is overlain by a poorly fossiliferous bed at the youngest seam of lignite and the ostracodes (mostly shallow marine) have been found above as well as below it (Bhandari et al. 2005). The *N. burdigalensis* horizon in the mine section thus represents the peak of the Early Eocene transgression in the Cambay Basin. Ostracode assemblage reported from the beds between Lignite 1 and Lignite 2 in Vastan Mine section suggests deposition in a marginal to very shallow marine environment (Bhandari et al. 2005). Sahni et al. (2006) suggested that the Vastan lignite probably formed in a back barrier lagoon which was open to intermittent marine influxes as exemplified by the cyclic occurrence of coal and marine and non-marine biota in the successively younger beds.

MATERIAL AND METHODS

For extraction of palynomorphs and the organic particles standard techniques were followed (Traverse 1988). Crushed shale samples were kept in 40% hydrofluoric acid for 3–4 days and after washing were sieved with 400 mesh (38 µm). Carbonaceous shale samples were treated with commercial nitric acid for 24 hours whereas, those having calcareous contents were first kept in concentrated hydrochloric acid for 12 hours and were then treated with hydrofluoric acid. Lignite samples were kept in concentrated nitric acid for 24–36 hours and were treated with solution of potassium hydroxide (5–15%) for 2–5 minutes. To recover Dispersed Organic Matter, samples were treated with concentrated hydrochloric acid for 12 hours, washed with water 2–3 times and kept in

40% hydrofluoric acid for 3–4 days. Lignite samples were kept in commercial nitric acid for 12 hours, sieved with 400 mesh and were treated with ammonia for 2–3 minutes. Water-free macerated residue was mixed with a few drops of polyvinyl alcohol, spread uniformly over the cover glass, dried in oven for about thirty minutes and mounted in Canada balsam. Microfloral elements were distinguished following artificial system of classification proposed by Potonié and Kremp (1955, 1956). Frequency was determined by counting 200 palynofossils and 500 organic matter particles in each sample.

PALYNOFLORAL COMPOSITION

A palynofloral assemblage comprised of pteridophytic spores, angiospermous pollen, dinoflagellate cysts and fungal remains was recorded. Results dealing with the dinoflagellate cysts (recorded from the samples 12, 13, 16, 17, 20, 21, 23, 24 and 25) have already been published (Garg et al. 2008). Fungal remains have not been included in present communication and have been considered for interpretative purposes only. Palynofossils assigned to 7 genera, 15 species have been ascribed to pteridophytic spores and 19 genera, 34 species to angiospermous pollen. Spores of the family Schizaeaceae (*Lygodiumsporites* spp.) and Osmundaceae (*Todisporites* spp.) are profusely recorded. Assemblage is dominated by Angiospermous pollen but those of the families Arecaceae and Bombacaceae are abundant. Pollen grains of Arecaceae have been assigned to different species of *Palmidites*, *Spinomonosulcites*, *Longapertites*, *Spinizonocolpites*, *Acanthotricolpites*, and *Echimonoporopollis grandiporus*. Pollen grains of Bombacaceae are ascribed to *Lakiapollis ovatus*, *Tricolporopollis matanomadhensis*, and *Dermatobrevicolporites dermatus*. The assemblage is constituted by following palynotaxa:

Pteridophytic spores

Cyathidites australis Couper 1953
Biretisporites bellus Sah & Kar 1969
Biretisporites convexus Sah & Kar 1969
Dictyophyllidites laevigatus Kar 1985
Lygodiumsporites eocenicus Dutta & Sah 1970
Lygodiumsporites lakiensis Sah & Kar 1969
Lygodiumsporites pachyexinus Saxena 1978
Osmundacidites kutchensis Sah & Kar 1969
Todisporites flavatus Sah & Kar 1969
Todisporites kutchensis Sah & Kar 1969
Todisporites major Couper 1958
Todisporites plicatus Sah & Kar 1969
Todisporites subtriangulatus Mathur & Mathur 1980
Cheilanthoidspora miocenica Kar & Jain 1981
Cheilanthoidspora monoleta Sah & Kar 1974

Angiosperm pollen

Monocolpate/Monosulcate

Arecipites bellus Sah & Kar 1970
Liliacidites magnus Jain et al. 1973
Longapertites discordis Frederiksen 1994
Longapertites punctatus Frederiksen 1994
Matanomadhiasulcites kutchensis (Saxena) Kar 1985
Matanomadhiasulcites major (Singh) Saxena & Khare 2004
Matanomadhiasulcites maximus (Saxena) Kar 1985
Neocouperipollis robustus (Saxena) Saxena & Khare 2004
Palmidites naviculus Kar & Saxena 1981
Palmidites maximus Couper 1953
Retimonosulcites ovatus (Sah & Kar) Kar 1985
Spinomonosulcites achinatus (Sah & Kar) Singh & Misra 1991
Spinomonosulcites brevispinosus (Biswas) Kumar 1994

Zonisulcate

Proxapertites marginatus (Venkatachala & Kar) Singh 1975
Proxapertites cursus van Hoeken-Klinkenberg 1966
Spinizonocolpites bulbospinosus Singh 1990
Spinizonocolpites venkatachalae Saxena & Khare 2004
Spinizonocolpites wodehousei Singh 1990

Tricolpate:

Verrutricolpites longicolpus (Biswas) Mandal & Guleria 2006

Tricolporate

Dermatobrevicolporites dermatus (Sah & Kar) Kar 1985
Lakiapollis ovatus Vankatachala & Kar 1969
Palaeosantalaceaepites reticulates Samant & Phadtare 1997
Psilatricolporites sagittatus Samant & Phadtare 1997
Psilatricolporites sahii Saxena & Khare 2004
Tricolporopollis matanomadhensis (Venkatachala & Kar) Tripathi & Singh 1985
Tricolporopollis ruber Dutta & Sah 1970

Polycolporate

Polygalacidites minutus Samant & Phadtare 1997

Monoporate

Echimonoporopollis grandiporus, Saxena, Khare & Mishra 1991

Triporate

Acanthotricolpites complexus Singh & Misra 1991
Acanthotricolpites intermedius Singh & Misra 1991
Acanthotricolpites karii Saxena & Khare 2004
Acanthotricolpites kutchensis (Venkatachala & Kar) Singh & Misra 1991
Acanthotricolpites multitypicus Singh & Misra 1991
Acanthotricolpites tiruchirapalliensis Saxena & Khare 2004

PALYNOFLORAL COMPARISON

Palynological reports from Vastan lignite are few (Mandal & Guleria 2006, Garg et al. 2008, and Dutta et al. 2012). Study of Mandal and Guleria (2006) is based on ten samples (nine from lower and one from upper lignite seam). Present study is based on samples representing all lithologies of the seam. Palynotaxa common to the assemblage described by Mandal and Guleria (2006) and that recorded during the present studies are: *Lygodiumsporites lakiensis*, *Cheilanthoidspora* spp., *Matanomadhiasulcites* spp., *Arecipites bellus*, *Spinomonosulcites achinatus*, *Verrutricolpites longicolpus*, *Tricolporopollis matanomadhensis*, *Lakiapollis ovatus*, *Acanthotricolpites kutchensis* and *Acanthotricolpites intermedius*. Some palynological works have been carried out on contemporaneous sediments exposed in open-cast lignite mines of Rajpardi (Kar & Bhattacharya 1992, Kumar, 1996, Samant & Phadtare 1997) and Bhavnagar (Samant 2000). These are located in the southern and western parts of Cambay Basin, Gujarat. Spore/Pollen genera commonly occurring in the present assemblage and that from Rajpardi are: *Biretisporites* spp., *Cheilanthoidspora* spp., *Todisporites* spp., *Lygodiumsporites* spp., *Arecipites* spp., *Retimonosulcites* spp., *Matanomadhiasulcites* spp., *Spinizonocolpites* spp., *Spinomonosulcites* spp., *Lakiapollis ovatus*, and *Polygalacidites* sp. Pollen genera common between the Bhavnagar assemblage and the present assemblage are: *Lygodiumsporites*, *Todisporites*, *Arecipites*, *Cupanidites*, *Echitriporites*, *Longapertites*, *Lakiapollis*, *Polygalacidites*, *Proteacidites*, and *Spiniznocolpites*. Differences between the two assemblages are also quite obvious. Conspicuous high frequency of different species of *Acanthotricolpites* and *Spinizonocolpites* in the present assemblage is not noticeable in Rajpardi and Bhavnagar assemblages.

Palynofloras from Early Eocene Naredi Formation, Kutch, Gujarat (Venkatachala & Kar 1969, Kar 1978, 1985) are rich and have many forms which have also been recorded during the present studies. The common palynotaxa are: *Lygodiumsporites lakiensis*, *Todisporites major*, *Arecipites bellus*, *Spinizonocolpites* spp., and *Lakiapollis ovatus*. Many taxa recorded from Late Palaeocene to Early Eocene sequences of Barmer, Rajasthan (Tripathi 1995, Tripathi et al. 2003, 2009, Tripathi & Srivastava 2010) are also recorded from Cambay Shale, Vastan. Species which share their presence in assemblages of both the areas belong to genera *Lygodiumsporites eocenicus*, *Lygodiumsporites lakiensis*, *Todisporites kutchensis*, *Todisporites major*, *Arecipites bellus*, *Longapertites discordis*, *Longapertites punctatus*, *Spinizonocolpites bulbospinosus*, *Spinizonocolpites venkatachalae*, *Spinomonosulcites achinatus*, *Spinomonosulcites brevispinosus*, *Acanthotricolpites complexus*, *A. kutchensis*, and *A. intermedius.* The Vastan assemblage differs from Barmer assemblage in having rich representation of different species of *Todisporites*, *Osmundacidites*, *Cheilanthoidspora*, *Lakiapollis*, *Tricolporopollis*, *Dermatobrevicolporites*, and *Acanthotricolpites*.

QUANTITATIVE REPRESENTATION OF PALYNOFOSSILS

Based on frequency of individual palynotaxa (Table 1), general quantitative assessment of the palynoflora has been made (Fig. 4). 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. Amongst the Pteridophytes, the spores of the families Osmundaceae (*Osmundacidites* spp., *Todisporites* spp.) and Schizaeaceae (*Lygodiumsporites* spp.,) are most common. Besides these, a spore genus of unknown affinity *Cheilanthoidspora* is moderately registered in some of the samples. Amongst the angiosperms, pollen grains having affinity with the family Bombacaceae are most frequent and are present throughout the section. These pollen grains have been described as *Dermatobrevicolporites dermatus*, *Tricolporopollis matanomadhensis* and *Lakiapollis ovatus*. Of these, *Lakiapollis ovatus* is most abundantly recorded. Pollen grains showing affinity with the family Arecaceae are represented by *Spinizonocolpites* spp., *Spinomonosulcites* spp. and *Acanthotricolpites* spp. In lower part of the section *Acanthotricolpites* spp. are abundant. Pollen grains of the families Liliaceae (*Retimonosulcites ovatus* and *Liliacidites magnus*) and Annonaceae (*Matanomadhiasulcites kutchensis*) occur in

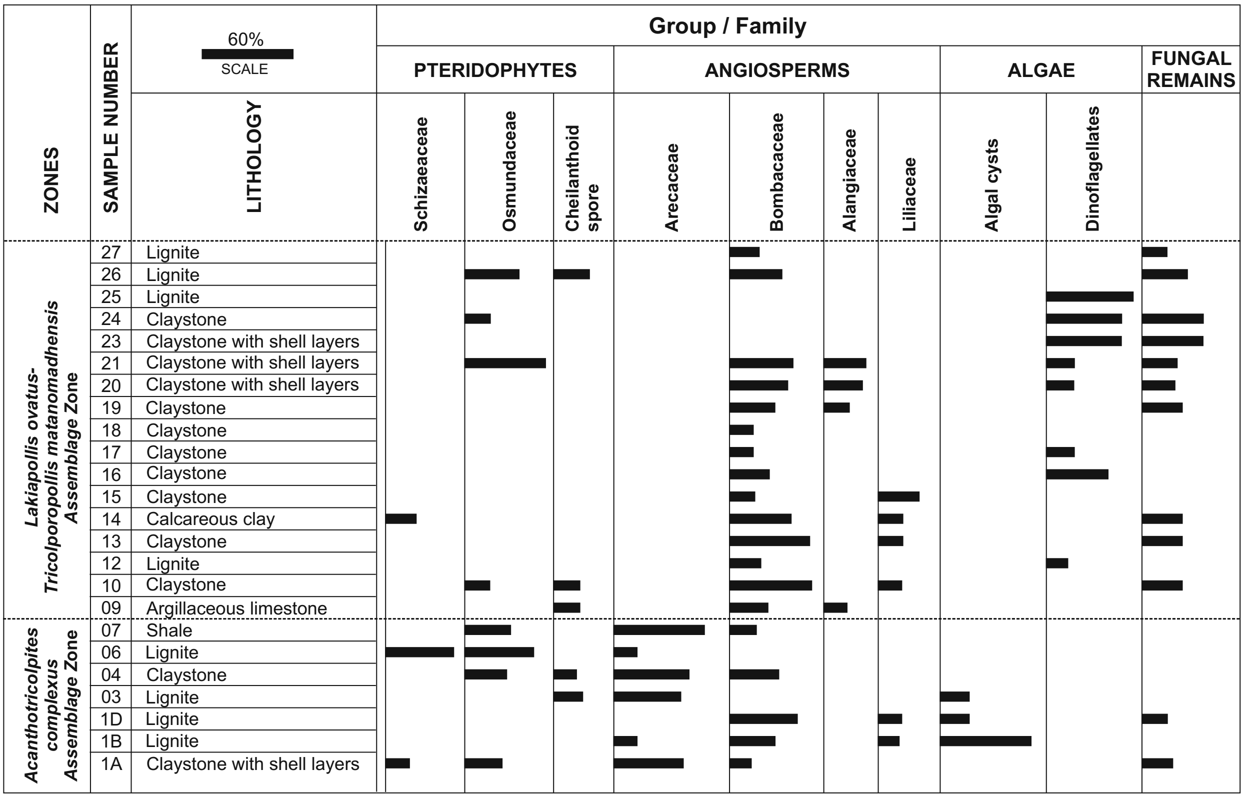

Fig. 4. Quantitative representation of palynoflora

moderate frequency throughout the sequence. Three samples representing the lowermost part of the section show high frequency of algal cysts whereas, the dinoflagellate cysts dominate in upper part.

BIOSTRATIGRAPHIC ZONATION

Table 1 summarizes the frequency of stratigraphically significant palynotaxa which have been categorized into six classes viz., Rare (1–3%), Frequent (4–10%), Profuse (11–19%), Abundant (20–29%), Dominant (30–50%) and over dominant (51–80%). Distribution and abundance of angiospermous palynotaxa allow division of the studied Cambay Shale succession into two formal palynozones which are named after the most dominantly represented taxon/taxa of the zone (Fig. 4). In the order of Stratigraphy these are:

1. *Acanthotricolpites complexus* Assemblage Zone

2. *Lakiapollis ovatus – Tricolporopollis matanomadhensis* Assemblage Zone

Characteristic features of these zones are as follows:

1. *Acanthotricolpites complexus* Assemblage Zone

Type Locality. Vastan lignite mine, Surat District, Gujarat.

Lithology. The dominant lithology of this cenozone is lignite. Other lithologies of the zone are claystone with shell layers, claystone and shale. Thickness of zone is about 6 metres.

Characteristic palynotaxa of the zone. *Biretisporites bellus*, *B. convexus*, *Todisporites* spp., *Cheilanthoidspora monoleta*, *C. miocenica*, *Matanomadhiasulcites kutchensis*, *M. major*, *Spinomonosulcites brevispinosus*, *S. achinatus*, *Echimonoporopollis grandiporus*, *Acanthotricolpites* spp.

Palynotaxa restricted to the zone. *Matanomadhiasulcites major*, *Spinomonosulcites achinatus*, *Proxapertites marginatus*, *Echimonoporopollis grandiporus*, *Acanthotricolpites* spp.

Remarks. The zone is characterized by the high frequency of different species of *Acanthotricolpites* in general and *A. kutchensis* in particular.

Table 1. Frequency of palynotaxa in samples from Vastan Lignite Mine, Cambay Basin, Western India

TAXA	SAMPLE NUMBER																
	1A	1B	1D	4	6	9	10	13	15	16	18	20	21	23	24	25	26
Biretisporites bellus					+												
Dictyophyllidites laevigatus			+				+					×					×
Lygodiumsporites lakiensis					×			+									
Lygodiumsporites pachyexinus			+		+												
Lygodiumsporites eocenicus	+				×							×	+				+
Osmundacidites kutchensis	+			+													+
Todisporites flavatus					+												+
Todisporites kutchensis					★								✦		+		
Todisporites major	+			+	×		+						+				×
Todisporites minor					×												
Todisporites plicatus					×												+
Cheilanthoidspora miocenica				+			+										+
Cheilanthoidspora monoleta				×		+											+
Liliacidites magnus							+										
Matanomadhiasulcites kutchensis		×	+				+	+	×		+	+	+				
Matanomadhiasulcites major		+															
Matanomadhiasulcites maximus		+										+					
Retimonosulcites ovatus							+				+	+					
Spinomonosulcites achinatus					+												
Spinomonosulcites brevispinosus	+			+	+	+								+			
Proxapertites marginatus	+																
Lakiapolleis ovatus	+	★	■	★		×	✷	✷	✦	×	+	✦	✦				✦
Tricolpopollis matanomadhensis		×	✦						+								×
Psilatricolporites sahii							+	+									
Dermatobrevicolporites dermatus						+	+					×					
Acanthotricolpites brevispinosus				×													
Acanthotricolpites bulbospinosus				×													
Acanthotricolpites complexus	×			★													
Acanthotricolpites intermedius	×			★													
Acanthotricolpites karii				×													
Acanthotricolpites kutchensis	+	+		✦	+												
Acanthotricolpites robustus				✦	×												
Proteacidites protrudus			+														
Echimonoporopollis grandiporus	×			✦													
Dinoflagellate cysts								+		■		+	+	✷	✷	✷	
Algal cysts		✷	×														
Fungal remains	×		+				×	×	✦		×	+	+	✦	✦		★

+ Rare: 1–3%	✦ Abundant: 20–29%
× Frequent: 4–10%	■ Dominant: 30–50%
★ Profuse: 11–19%	✷ Overdominant: 51–80%

2. ***Lakiapollis ovatus–Tricolporopollis matanomadhensis*** **Assemblage Zone**

Type Locality. Vastan lignite mine, Surat District, Gujarat.

Lithology. The litho-succession representing this part of the zone is constituted by lignite, calcareous clay, carbonaceous clay, claystone, molluscan shell layers. Thickness of the zone is about 24 metres.

Characteristic palynomorphs of the cenozone. *Dermatobrevicolporites dermatus*, *Psilatricolporites sahii*, *Retimonosulcites ovatus*, *Lakiapollis ovatus*, *Tricolporopollis matanomadhensis*, *Muratodinium fimbriatum*, *Polysphaeridium subtile*, *Thallasiphora pela-*

gic, *Lanternosphaeridium lanosum*, *Kenleya leptocerrata*, and *K. lophophora*.

Palynotaxa restricted to the zone. *Retimonosulcites ovatus*, *Dermatobrevicolporites dermatus*, *Psilatricolporites sahii.*

Remarks. The zone is marked with high frequency of *Matanomadhiasulcites* spp. *and Lakiapollis ovatus*. Marine influence during sedimentation of this part of the section is evident by abundance of dinoflagellate cysts. The zone is also characterized by high frequency of fungal remains.

PALAEOECOLOGIC AND PALAEOCLIMATIC INTERPRETATIONS

Recorded palynofossils along with their affinity with extant plants/families and their present-day distribution is given in Table 2. Pteridophytic spores present in the assemblage show morphological resemblance with the genera/families presently confined to tropical to sub-tropical regions. Some of these are cosmopolitan in distribution. Members of the

Table 2. Palynotaxa from Vastan Lignite Mine section, Cambay Basin along with present-day distribution

Families/Genera	Palynotaxa	Present-day distribution
Cyatheaceae/ Diksoniaceae	*Cyathidites australis*	Tropical to sub-tropical, tree fern of thick tropical forest
Matoniaceae	*Biretisporites bellus*, *B. convexsus*	Tropical to sub-tropical, sub aquatic to swampy
Dictyophyllaceae (*Dictyophyllum*)	*Dictyophyllidites laevigatus*	Cosmopolitan
Schizaeaceae	*Lygodiumsporites eocenicus*, *L. lakiensis*, *L. pachyexinus*	Tropical to subtropical, climbing fern
Osmundaceae	*Osmundacidites kutchensis*	Tropical to sub-tropical, sub-aquatic to swampy
	Todisporites flavatus, *T. kutchensis*, *T. major*, *T. plicatus*, *T. subtriangulatus*	
Cheilanthoid group of ferns (affinity unknown)	*Cheilanthoidspora miocenica*, *C. monoleta*	Unknown
Arecaceae	*Arecipites bellus*	Tropical to sub-tropical
	Palmidites maximus, *P. naviculus*,	
	Proxapertites marginatus, *Proxapertites cursus*	Chiefly tropical
	Neocouperipollis robustus,	*Nypa*-like pollen, back mangroove
	Spinizonocolpites bulbospinosus, *S. venkatachalae*, *S. wodehousei*,	
	Spinomonosulcites achinatus, *S. brevispinosus*	
	Echimonoporopollis grandiporus,	Tropical to subtropical
	Acanthotricolpites complexus, *A. intermedius*, *A. karii*, *A. kutchensis*, *A. multitypicus*, *A. tiruchirapalliensis*	Chiefly tropical
	Longapertites discordis, *L. punctatus*	Tropics of Malasia, Lowland evergreen palms
Liliaceae	*Liliacidites magnus*	Cosmopolitan
	Retimonosulcites ovatus	
Annonaceae	*Matanomadhiasulcites kutchensis*, *M. major* *M. maximus*	Tropical, Evergreen
Bombacaceae	*Dermatobrevicolporites dermatus*	Tropics, swampy evergreen forests
	Lakiapollis ovatus,	
	Tricolporopollis matanomadhensis	
Euphorbiaceae	*Tricolporopollis ruber*	
Rhizophoraceae	*Palaeosantalacepites reticulatus*	Tropical, true mangrove
Polygalaceae/ Xanthophyllaceae	*Polygalacidites minutus*	Cosmopolitan
Unknown	*Verrutricolpites longicolpus*	
Unknown	*Psilatricolporites sagittatus*, *P. sahii*	

family Osmundaceae and Schizaeaceae indicate warm and humid tropical climate. These also indicate prevalence of perennial water in their close vicinity. *Cyathea*, a tree-fern is indicator of a thick and closed tropical forest. Most dominant component of the palynoflora is represented by the angiosperms. Amongst these, pollen grains of the monocot family Arecaceae are registered in highest frequency. Different species of *Arecipites*, *Acanthotricolpites*, *Spinizonocolpites*, *Echimonoporopollis*, *Spinomonosulcites*, *Proxapertites*, *Palmidites*, and *Longapertites* represent the pollen grains of this family.

Numerous pollen grains of dicotyledonous taxa have also been recorded in the assemblage. These are assigned to the families Liliaceae, Bombacaceae, Annonaceae, Euphorbiaceae, Rhizophoraceae, and Polygalaceae. Of these, the pollen of Bombacaceae (*Dermatobrevicolporites dermatus*, *Tricolporopollis matanomadhensis*, and *Lakiapollis ovatus*) are the most frequent. These are the indicators of perennial fresh-water swamps. The prevalence of near deltaic to deltaic condition is strongly indicated by pollen of Rhizophoraceae (*Palaeosantalaceaepites reticulatus*). Existence of deltaic conditions is further confirmed by pollen having strong affinity with *Nypa* (species assigned to *Spinizonocolpites*, *Spinomonosulcites*, and *Neocouperipollis*). Fossil spore/pollen indicating different ecological groups are as follows:

Back mangrove and mangrove elements. *Spinizonocolpites* (Arecaceae, *Nypa*), *Palaeosantalaceaepites* (Rhizophoraceae)

Swamp and water-edge members. *Todisporites* (Osmundaceae), *Lygodiumsporites* (Schizaeaceae), *Dermatobrevicolporites*, *Lakiapollis*, *Tricolporopollis* (Bombacaceae, *Durio*), *Polygalacidites* (Polygalaceae)

Thick and closed forest elements. *Cyathidites* (Cyatheaceae), *Matanomadhiasulcites* (Annonaceae), *Proxapertites* (Arecaceae), *Longapertites* (Arecaceae), *Arecipites* (Arecaceae)

Water-shed zone members. *Biretisporites* (Matoniaceae)

VEGETATION SUCCESSION AND ENVIRONMENT OF DEPOSITION

Lower part of the succession is rich in pteridophytic spores of Osmundaceae and Schizaeaceae, pollen of the families Arecaceae and Bombacaceae and algal Cysts. Members of the family Osmundaceae grow in swamps and water edge environments whereas, the presence of Schizaeaceae indicates occurrence of thick forests in nearby area. Different species of *Acanthotricolpites* having affinity with Arecaceae (Venkatachala et al.1996) are abundant in lower part of the succession. These pollen indicate coastal environment. Profusely recorded fossil pollen *Lakiapollis ovatus* in the Vastan succession morphologically resemble with pollen of extant plant *Durio* (Bombacaceae) which is a member of Indo-Malayan tropics (Thanikaimoni et al. 1984). Plants of *Durio* grow in swampy evergreen forests. Accumulation of woody elements in the swamps of deposition site created anoxic bog conditions which were responsible for the deposition of organic rich sediments. Prevalence of similar conditions are inferred till the deposition of middle part of the sequence as the pollen grains of the family Bombacaceae continued to occur in high frequency up to this part. In general the middle part of the sequence is marked by impoverishment of pollen flora but the signature of marine incursions is evident due to presence of dinoflagellate cysts. The marine influence increased during the deposition of upper part of the sequence. This upper part is also characterized by presence of diverse fungal remains, mainly the fungal hyphae and spores, indicating the activity of saprophytic fungi. Generally the deltaic sediments provide such substrate (Traverse 1988). The middle and upper parts of the sequence are rich in pollen of the families Bombacaceae, Liliaceae, dinoflagellate cysts, and fungal remains.

Palynotaxa occurring in Vastan assemblage indicate tropical climate. Variations in taxa frequency provide evidence that plants growing within this broad climate occupied varied ecological niches. It is inferred that the lower part of Cambay Shale was deposited in coastal environment as the sediments of this part are very rich in pollen having affinity with Arecaceae whereas, upper part received more input from the nearby evergreen forests. Palaeoequatorial positioning of Indian subcontinent and global warming phase of early Palaeogene (PETM and EECO) during the deposition of studied succession were instrumental in the development of excessive warm and humid climate.

PALYNOFACIES STUDIES

In the lower part of the Vastan section the most dominant constituent of the organic matter is structured terrestrial material followed by biodegraded, amorphous and black debris (Fig. 5). Occurrences of such assemblages indicate that during deposition of this part large amount of terrestrial vegetal matter was incorporated. The middle part of the section is rich in biodegraded and amorphous organic matter followed by the structured terrestrial Organic Matter. In upper part of the section, reduced frequency of structured terrestrial matter was observed whereas, the biodegraded matter increased quantitatively. Based on such representation of organic matter it is inferred that during deposition of the middle part of the section anoxic conditions were set in and the upper part was deposited under the increased influence of anoxic conditions. General trend perceived through the organic matter studies in the sequence from lower to top strata is the increase in biodegraded and amorphous contents, more or less uniform representation of resinous contents and fluctuating frequency of spore/pollen (Fig. 5).

Quantitative analysis of organic matter contents recovered from various lithologies indicates that the structured terrestrial elements increase in frequency in claystone beds. Biodegraded organic matter contents are also represented in high frequency in claystone beds and in one of the lignite samples from top of the sequence. Amorphous contents are present in high frequency in lignite samples.

DISCUSSION

Many species of Spore/pollen genera assigned to *Cheilanthoidspora*, *Todisporites*, *Lygodiumsporites*, *Lakiapollis*, *Tricolporopollis*, *Dermatobrevicolporites*, and *Acanthotricolpites* reported from different Early Eocene

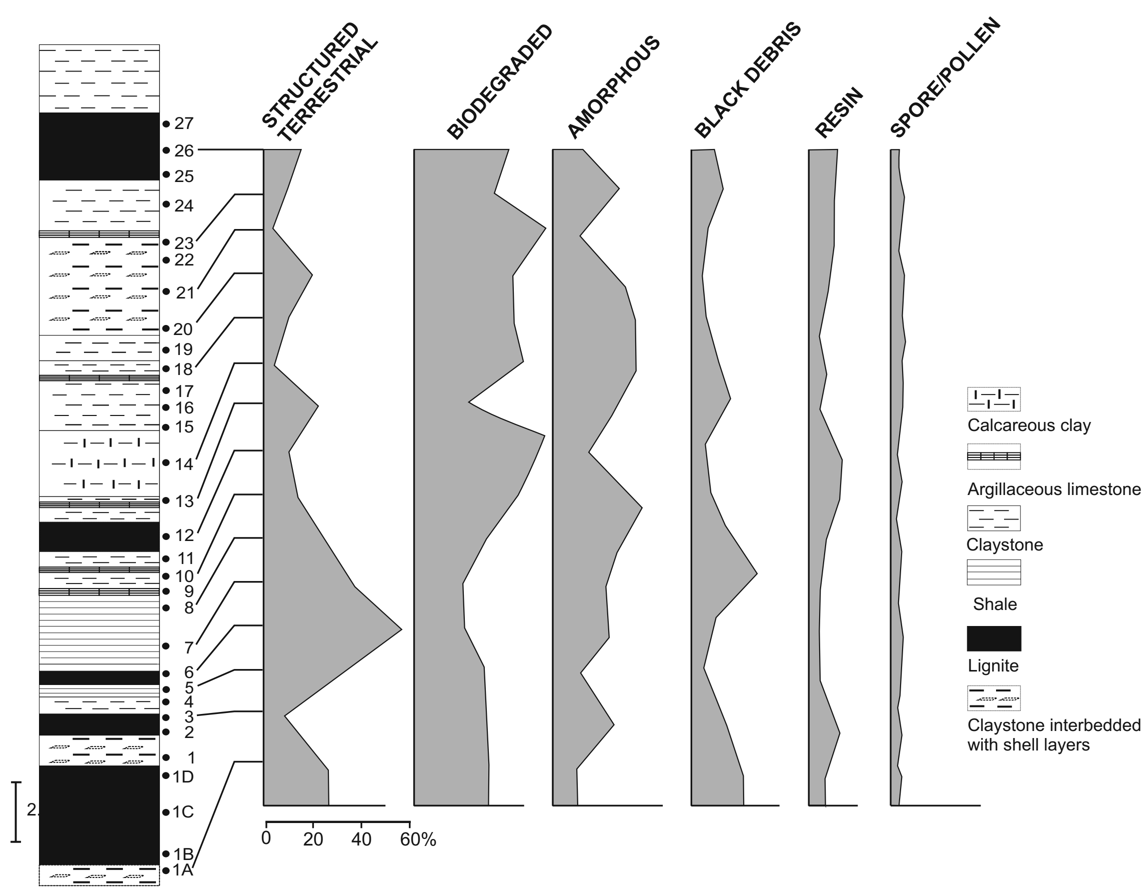

Fig. 5. Quantitative representation of Dispersed Organic Matter and spore/pollen

sedimentary sequences of India (Thanikaimoni et al. 1984, Kar 1985, Venkatachala et al. 1989, 1996) are also present in Vastan assemblage. In addition to these, the Vastan assemblage is closely similar to the Early Eocene flora described from western part of India particularly those from Kutch, Rajpardi, Vastan, and Bhavnagar (Kar & Bhattacharya 1992, Kumar 1996, Samant & Phadtare 1997, Samant 2000, Mandal & Guleria 2006).

Garg et al. (2008) described dinoflagellate cysts from the same levels of Vastan section. Most of these are long ranging, having their distribution throughout Palaeogene. However, presence of some marker taxa like *Muratodinium fimbriatum*, *Heteraulacacysta granulata*, and *Kenleyia* complex (*Kenleyia lophophora*, *K. lophocerata*) is significant for indicating the age of the investigated lignite bearing sequence. These taxa are known to occur in calcareous plankton and larger foraminifera zones identified in Late Palaeocene-Early Eocene succession from several areas in North Sea, northern Africa, Uzbekistan and New Zealand (Garg et al. 2008). *Muratodinium fimbriatum* is a global age marker with its FAD in Thanetian, the upper most NP9 nanoplankton zone (Stover et al. 1996). This species is recorded throughout the palynologically productive part of the present sequence and indicates an age not older than latest Thanetian which is equivalent to P5b and NP9 corresponding to the upper part of SBZ6 and basal SBZ7 larger foraminifera biozones.

In lower part of the studied sequence, presence of dinoflagellate cyst genera *Heteraulacacysta granulata* and *Operculodinium severinii* is noticed. These taxa are recorded along with *Muratodinium fimbriatum* from Late Palaeocene to Early Eocene of Imo Shale SW Nigeria (Jan du Chene & Adediran 1985). Different species of *Kenleyia*, predominantly a southern hemisphere genus, abundantly occur in middle part of the studied succession (Sample Nos. 13 and 16). *Kenleyia lophophora*, *K. lophocerata* have their FADs in basal Danian (Brinkhuis & Zachariasse 1988, Garg et al. 2006). The LAD of these taxa has recently been confirmed in Early Eocene of Tunisia and Uzbekistan with early P6 and NP10-NP11 zones corresponding to larger foraminifera zones SBZ7 and SBZ8 (Garg et al. 2008). The *Kenleyia* complex is most common in costal and neritic setting and is found to be abundant across P-E transition including PETM interval having preference for warm waters (Crouch et al. 2003). Upper part of the sequence is marked with the presence of *Lanternosphaeridium lanosum* indicating an age not younger than Middle Ypresian as its LAD occurs around 52 Ma (Stover et al. 1996). This corresponds tentatively to lower part of P7, NP12 and SBZ10 zones. Considering the distribution of dinoflagellate cysts, Garg et al. (2008) assigned Late Ilerdian to basal Cuisian (55–52 Ma) age to the studied sequence. Foraminiferal assemblages, recorded from multiple levels of Vastan Section (Sahni et al. 2006) are represented by tiny and juvenile forms assigned to *Gavelinella*, *Cibicidoides*, *Praebullina*, and *Bolivina*. One of the horizons has exceptional abundance of *Nummulites burdigalensis burdigalensis* which corresponds to shallow benthic zone SBZ10 of basal Cuisian age. This zone is equivalent to the Planktonic foraminiferal zone P6b of Middle Ypresian. Terrestrial palynomorphs confirm that the studied sequence of Vastan, Cambay Basin, western India is Thanetian to Ypresian in age. This age determination is supported by previous studies of dinoflagellate cysts and foraminifera.

CONCLUSIONS

1. Palynoflora of the studied lignite-bearing succession is dominated by angiospermous pollen grains, of which, those having affinity with the families Arecaceae and Bombacaceae are abundant.

2. The overall assemblage indicates a warm and exceptionally humid climate of coastal zone, with a tropical rainforest in the vicinity of the depositional environment.

3. The studied sequence is palynologically divided into two zones. The lower zone is rich in pteridophytic spores and pollen of the family Arecaceae whereas, the upper zone is dominated by pollen of the family Bombacaceae and dinoflagellates.

4. Terrestrial palynomorphs confirm that the studied sequence from Cambay Basin, western India is Thanetian to Ypresian in age. This aligns well with previous studies on dinoflagellates and foraminiferal assemblages.

5. Based on the studies of Dispersed Organic Matter, it is inferred that lower and middle parts of the sequence were deposited under

less anoxic conditions whereas, the upper part was deposited under the influence of completely anoxic condition.

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PLATES

Plate 1

1. *Arecipites bellus* Sah & Kar 1970, slide No. BSIP 13541, Coordinates: 74.3 × 97.5
2. *Longapertites discordis* Frederiksen 1994, slide No. BSIP 13549, Coordinates: 58.5 × 97.3
3. *Longapertites punctatus* Federiksen 1994, slide No. G05/26/3/1 BSIP 13553, Coordinates: 49.3 × 88.5
4. *Matanomadhiasulcites kutchensis* (Saxena) Kar 1985, slide No. BSIP 13552, Coordinates: 43.3 × 89.6
5. *Spinizonocolpites bulbospinosus* Singh 1990, slide No. BSIP 13548, Coordinates: 56.2 × 98.4
6. *Spinizonocolpites venkatachalae* Saxena & Khare 2004, slide No. BSIP 13562, Coordinates: 68.3 × 98.7
7. *Spinizonocolpites wodehousei* Singh 1990, slide No. BSIP 13572, Coordinates: 67.3 × 79.5
8. *Spinomonosulcites achinatus* (Sah & Kar) Singh & Misra 1991, slide No. BSIP 13564, Coordinates: 67.2 × 85.4 BSIP 13551, Coordinates: 48.3 × 87.5
9. *Spinomonosulcites brevispinosus* (Biswas) Kumar 1994, slide No. BSIP 13548, Coordinates: 47.3 × 67.5
10. *Verrutricolpites longicolpus* Mandal & Guleria 2006, slide No. BSIP 13558, Coordinates: 67.3 × 89.5
11. *Dermatobrevicolporites dermatus* (Sah & Kar) Kar 1985, slide No. BSIP 13565, Coordinates: 54.3 × 65.5
12. *Lakiapollis ovatus* Venkatachala & Kar 1969, slide No. BSIP 13556, Coordinates: 48.3 × 87.5

(Scale bars 10 μm)

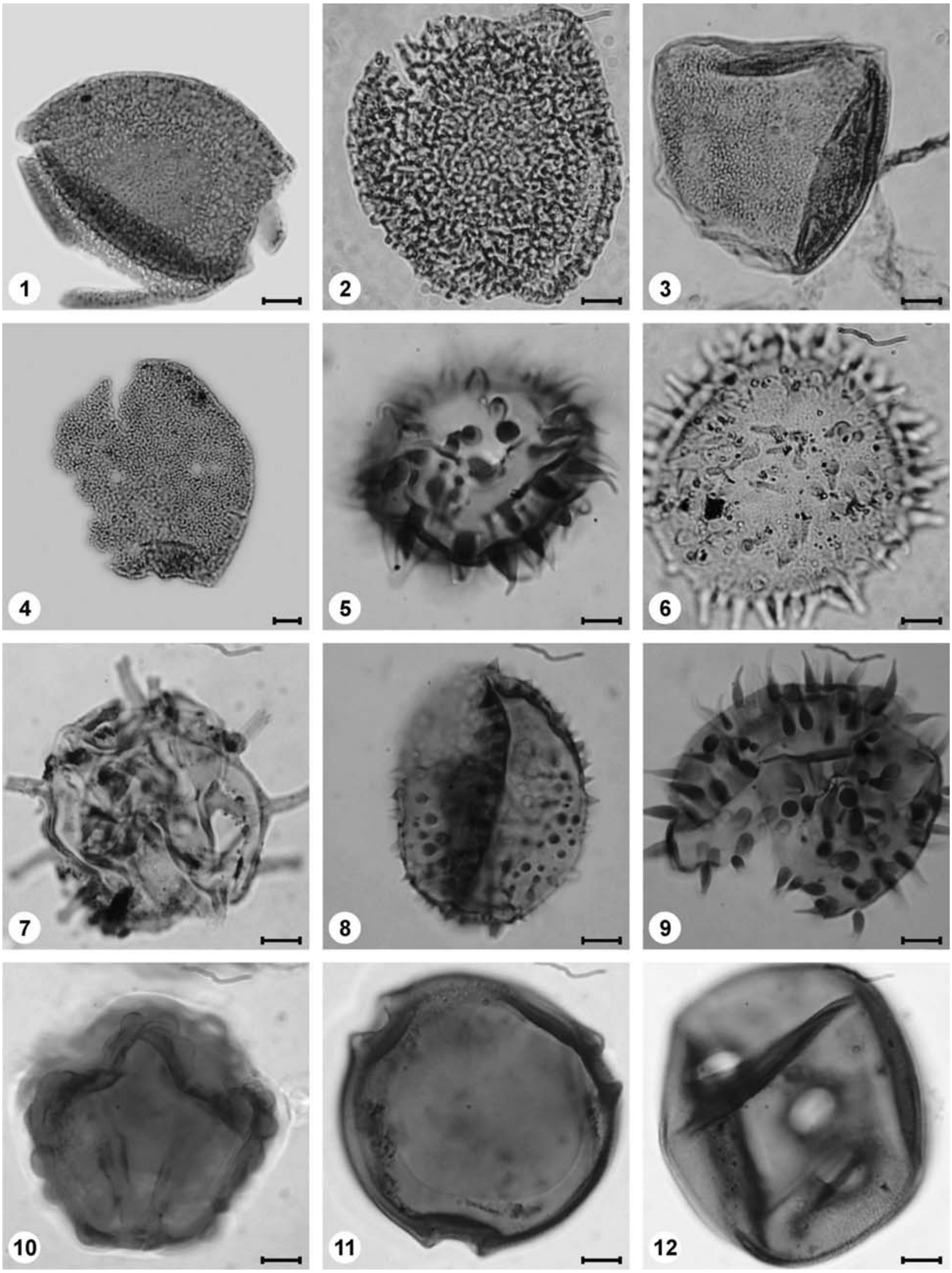
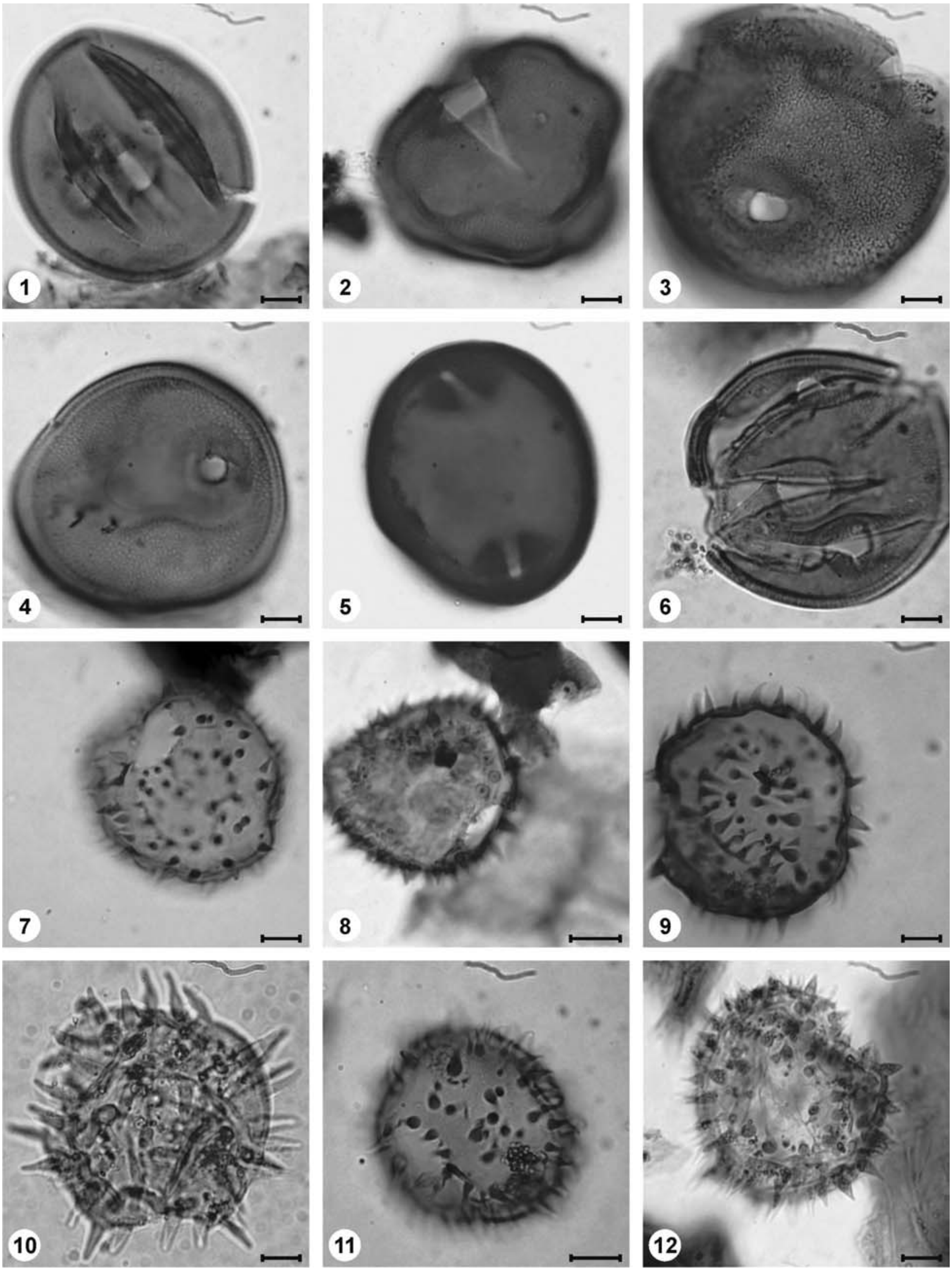


Plate 2

1. *Psilatricolporites sagittatus* Samant & Phadtare 1997, slide No. BSIP 13568, Coordinates: 47.8×76.6
2. *Psilatricolporites sahii* Saxena & Khare 2004, slide No. BSIP 13567, Coordinates: 48.7×73.5
3. *Tricolporopollis matanomadhensis* (Venkatachala & Kar) Tripathi & Singh 1985, slide No. BSIP 13569, Coordinates: 46.8×97.3
4. *Tricolporopollis rubra* (Dutta & Sah) Tripathi & Singh 1985, slide No. BSIP 13571, Coordinates: 58.2×89.3
5. *Paleosantalaceaepites* sp., slide No. BSIP 13566, Coordinates: 65.6×109.7
6. *Polygalacidites minutus* Samant & Phadtare 1997, slide No. BSIP 13568, Coordinates: 48.3×87.8
7. *Echimonoporopollis grandiporus* Saxena, Khare & Mishra 1991, slide No. BSIP 13556, Coordinates: 66.4×107.5
8. *Acanthotricolpites complexus* Singh & Misra 1991, slide No. BSIP 13555, Coordinates: 46.4×89.5
9. *Acanthotricolpites intermedius* Singh & Misra 1991, slide No. BSIP 13555, Coordinates: 68.3×97.5
10. *Acanthotricolpites karii* Saxena & Khare 2004, slide No. BSIP 13572, Coordinates: 48.3×87.5
11. *Acanthotricolpites kutchensis* (Venkatachala & Kar) Singh & Misra 1991, slide No. BSIP 13557, Coordinates: 65.2×98.5
12. *Acanthotricolpites multitypicus* Singh & Misra 1991, slide No. BSIP 13550, Coordinates: 78.4×98.6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