Geologica Acta, Vol.7, Nos 1-2, March-June 2009, 147-160
DOI: 10.1344/105.000000275
Available online at www.geologica-acta.com

geologica acta

Palynology of Lower Palaeogene (Thanetian-Ypresian) coastal deposits from the Barmer Basin (Akli Formation, Western Rajasthan, India): Palaeoenvironmental and palaeoclimatic implications

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ABSTRACT

The 32-m thick sedimentary succession of the Paleocene-Eocene Akli Formation (Barmer basin, Rajasthan, India), which is exposed in an open-cast lignite mine, interbed several lignite seams that alternate with fossiliferous carbonaceous clays, green clays and widespread siderite bands and chert nodules. The palynofloral assemblages consist of spore, pollen and marine dinoflagellate cysts that indicate a Thanetian to Ypresian age. The assemblage is dominated by angiospermic pollen and specimens showing affinity with the mangrove Palm *Nypa* are also very abundant. The *Nypa*-like pollen specimens exhibit a wide range of morphological variation, some of the recorded morphotypes being restricted to this Indian basin. Preponderance of these pollen taxa indicates that the sediments were deposited in a coastal swamp surrounded by thick, *Nypa*-dominated mangrove vegetation. The dispersed organic matter separated from macerated residues indicates the dominance of anoxic conditions throughout the succession, although a gradual transition to oxic conditions is recorded in the upper part.

KEYWORDS **Mangrove pollen. *Nypa*. Thanetian-Ypresian. India.**

INTRODUCTION

During the last two decades abundant palynological and palaeontological data have been obtained from Lower Palaeocene to Lower Eocene lignite bearing sedimentary sequences of western Rajasthan. Most of the palynological reports were chiefly restricted to the description of palynotaxa (Bose, 1952; Rao and Vimal, 1950, 1952; Jain *et al*., 1973; Lukose, 1974; Sah and Kar, 1974; Naskar and Baksi, 1978; Kar, 1995, 1996; Ambwani and Singh, 1996). Singh and Dogra (1988), taking into account the distribution of palynotaxa and marine fauna, attempted the correlation of the Palaeocene sequences of Rajasthan with other coeval sequences in India. Based on Upper Palaeocene-Lower Eocene palynofloral assemblages from bore-holes drilled near Barmer, Tripathi (1994, 1995, 1997) defined two informal palynozones that allowed distinction of the Palaeocene and Eocene deposits. Kar and Sharma (2001) carried out palynostratigraphical studies from Upper Palaeocene and Lower Eocene subsurface sediments of the Bikaner-Nagaur Basin. Tripathi *et al*. (2003) published a comprehensive palynological report from the Thumbli Member of the Akli Formation in Barmer and dated the sequence as Late Palaeocene.

This study deals with the Lower Palaeogene lignite bearing sequence (Akli Formation) exposed in open-cast lignite mine near Giral in the Barmer District, Rajasthan (Fig. 1). The study of this section was undertaken with the objectives of refining the biostratigraphy of the sequence and interpreting the environment of deposition by means of palynological and palynofacies analyses. Since detailed taxonomic aspects of palynotaxa do not constitute the main objective of this paper only lists of taxa will be provided, although relevant distinguishing features of some significant palynotaxa will be described where necessary.

GEOLOGICAL SETTING

Being part of the Indian shield, the sedimentary record in Rajasthan covers a time span from the Early Archean to recent, though most of the outcrops in the area are Precambrian in age. Intracratonic sedimentation commenced during Jurassic (Sinha-Roy et al., 1998) and resulted in the development of distinct basins in the Jaisalmer, Barmer and Bikaner-Nagaur regions, covering an area of about 120,000 km^2.

In the northern part of the Barmer Basin the Fatehgarh Formation is the oldest Tertiary unit (Fig. 2). The base of this formation corresponds to a conglomerate overlain by sandstones, bentonite clays, phosphatic sandstones and phosphatic mudstones. The unconformably overlying Mataji Ka Dunger Formation is constituted of cyclically arranged deltaic claystones and siltstones. The Akli Formation unconformably overlies the Mataji Ka Dunger Formation. In the central part of the basin it is characterized by a fine to very fine grained lithology rich in bentonites, phosphate beds and siliceous rocks.

In the study area (26° 03' N and 71° 15' E) the Akli Formation is about 32-m thick and starts with a shale-rich interval characterized by abundant burrows and siderite nodules (Fig. 3). The occurrence of *Assilina daviesi* in the basal part of this formation suggests upper Ypresian planktonic foraminiferal zones P7-P9 (Sahni et al., 2004). The basal shale is overlayed by alternating lenses of friable, grey-black lignite, greenish grey clays and carbonaceous clays that yield abundant plant remains and gastropod bearing nodula, brachiopods and benthic foraminifers (Sahni et al., 2004). Sideritic and chert layers are also common and the upper shale horizons interbedded with poorly bedded, pale bluish-grey bentonites that bear ferruginous nodules, chert and phosphate cores. These varied deposits are arranged in 2-3 m thick cycles that begin with bentonites, follow with bituminous claystones and end up with lignites (Fig. 3).

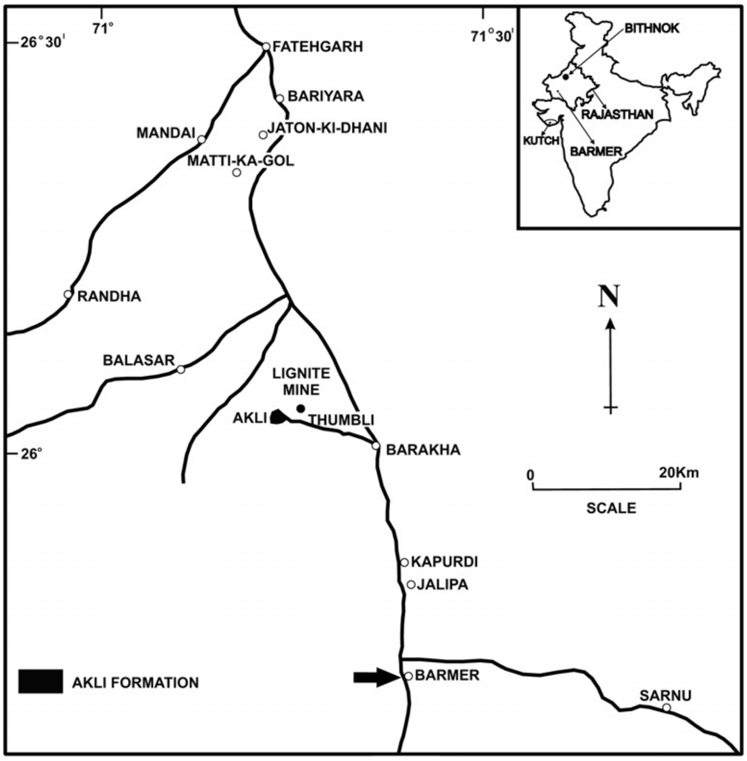

FIGURE 1 | **Location map of the Akli Formation lignite open pits in the Barmer Basin (After Sisodia and Singh, 2000). Other palynological sites mentioned in the text are also shown.**

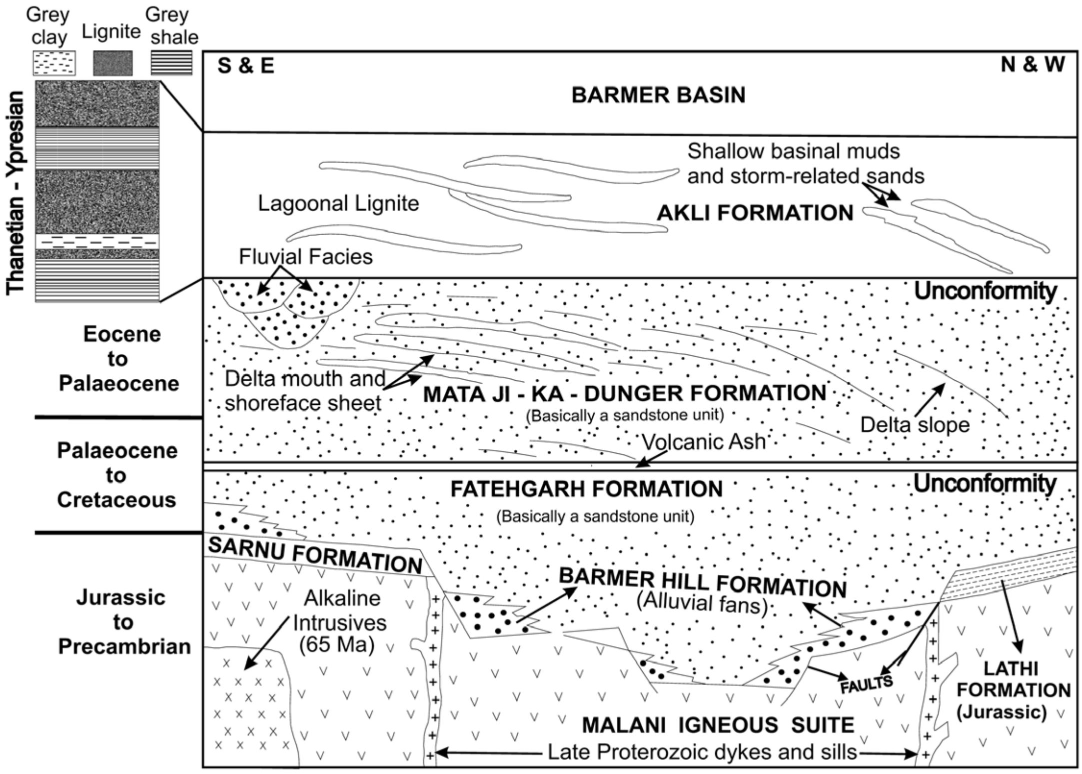

FIGURE 2 **Lithostratigraphy of the the Barmer Basin (after Sisodia and Singh, 2000).**

MATERIAL AND METHODS

Thirty eight samples were collected from the Akli Formation succession exposed in the lignite mine, 32 of which yielded palynological remains (Fig. 3). For the recovery of palynofossils, mineral components were first removed with specific acids: the most common silicates were removed with 40-60% HF; carbonates, commonly found as calcite, were dissolved in HCl; sulphates, sulphides and carbon contents are soluble in concentrated HNO_3. The macerated residues were checked under the microscope for organic content. After this inspection, part of each sample was treated with an alkaline solution of Na_2CO_3 or KOH, whose concentration and duration of treatment were decided on the basis of the organic content of each sample. Part of residue was left untreated with alkali for the study of dispersed organic matter. Very fine mineral particles mixed with the macerated residue were removed by density separation. These methods proved essential to separate and concentrate the spore/pollen fraction. The water-free macerated residue was mixed with a few drops of polyvinyl solution and was spread uniformly over a cover glass with the help of a glass rod. The cover glass was dried in an oven for about thirty minutes and was then mounted in Canada balsam. The prepared slides were kept in the oven at 50-60°C for 7-8 days.

Slides prepared from the productive samples were examined under the microscope for qualitative and quantitative assessment of palynofossils and organic matter. Distinguishable morphotypes were identified following the artificial system of classification and the abundance of each of them in the given amount of residue of every sample was determined by counting 200 palynotaxa. For palynofacies analysis organic matter types were categorized into three major groups: Group I was constituted by palynofossils (pollens, spores and algae); Group II included structured palynodebris, i.e. remains that clearly showed their organic structure but which were usually not taxonomically assignable (tracheids, cuticles, plant tissues); and Group III made up by structureless organic remains that did not show well-defined structures.

PALYNOLOGICAL ANALYSIS

Palynological assemblages of the Akli Formation

The palynological assemblage includes pteridophytic spores (5 genera and 7 species), angiospermic pollen (16 genera and 29 species) and dinoflagellate cysts (3 genera and 4 species). The assemblage is characteristically dominated by angiospermic pollen referable to the family Arecaceae. These forms have been ascribed to different

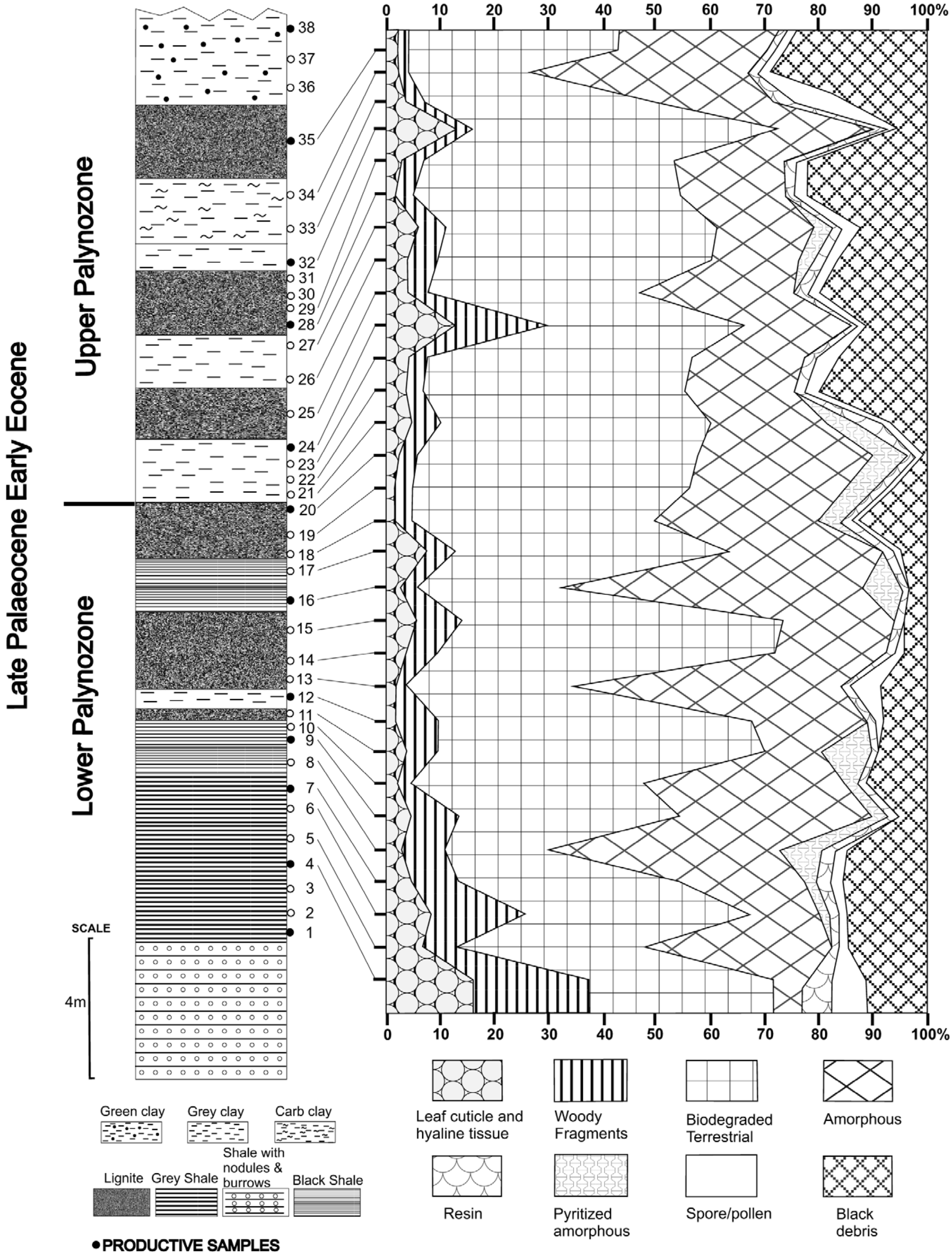

FIGURE 3 | **Stratigraphic log of the Akli Formation, showing location of samples and relative abundance of dispersed organic matter.**

species of *Spinizonocolpites, Kapurdipollenites, Retiverrumonosulcites, Acanthotricolpites, Clavadiporopollenites, Proxapertites, Palmidites* and *Palmaepollenites*. Species attributed to *Spinizonocolpites* (Fig. 4B-C) are spheroidal to ovoidal in shape, possess an extended sulcus and are provided with a spinose exine. Size of pollen varies between 50 and 70 μm. Shape and size of spines (5-15 μm) are variable, being straight to slightly curved at the tip and may exhibit a bulbous base. The inter-spinal area is smooth to reticulate. The two species of *Kapurdipollenites* (Fig. 4F-G) are also spherical to ovoidal in shape, possess an extended sulcus and range in size from 65 to 70 μm. Exine in these forms is provided with variety of sculptural elements like verrucae, gemmae, clavae and baculae.

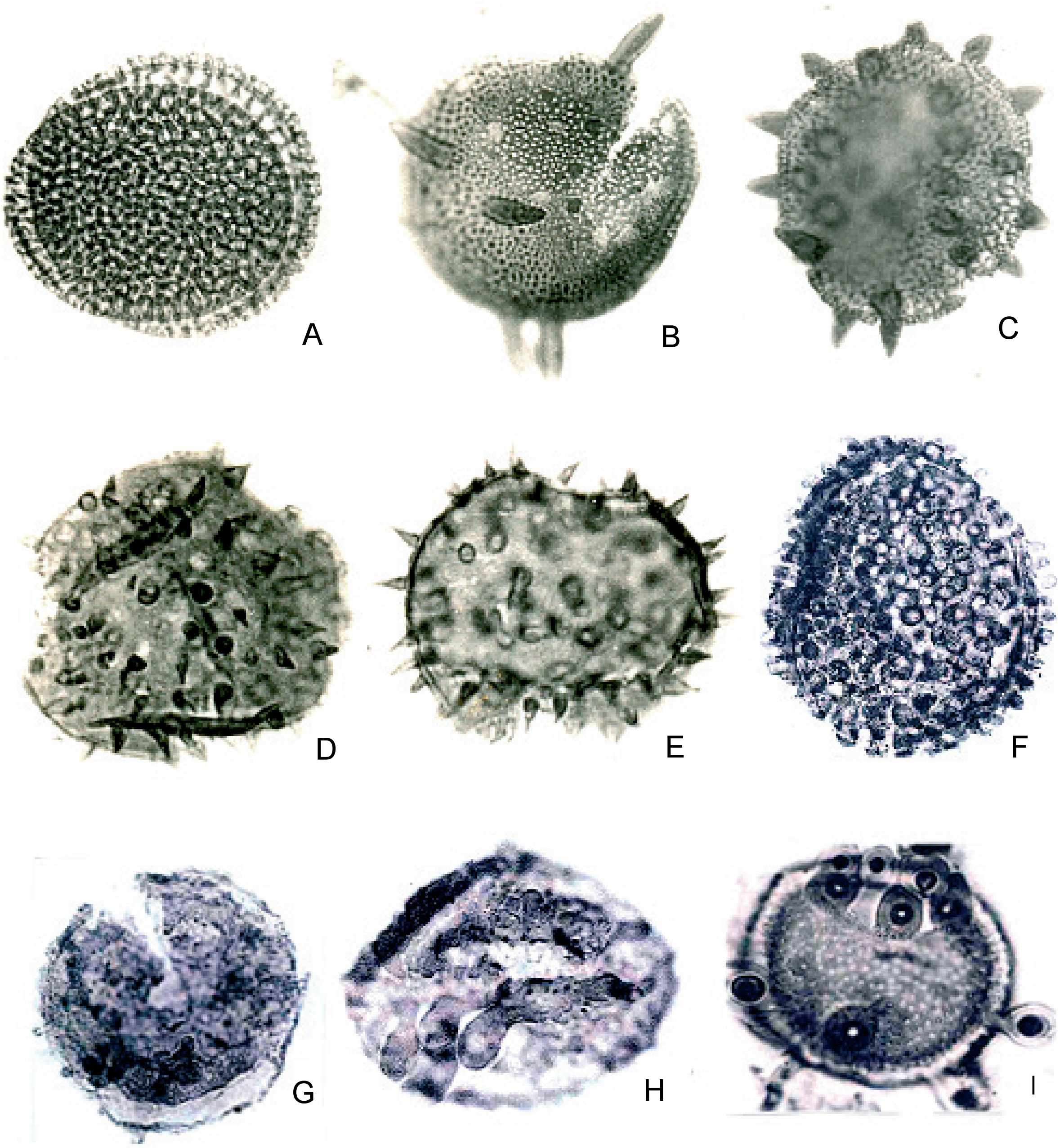

FIGURE 4 | **Selected examples of palynotaxa from the Akli Formation. A) *Proxapertites cursus* Muller, 1968; Size range 45-68 µm. B) *Spinizonocolpites baculatus* Muller, 1968; Size range 47-72 µm. C) *Spinizonocolpites echinatus* Muller, 1968; Size range 43-78 µm. D) *Acanthotricolpites kutchensis* (Kar and Kumar) A. Singh and Misra, 1991; Size range 46-78 µm. E) *Acanthotricolpites multitypicus* A. Singh and Misra, 1991; Size range 50-75 µm. F) *Kapurdipollenites gemmatus* Tripathi, 1994; Size range 50-75 µm. G) *Kapurdipollenites baculatus* Tripathi, 1994; Size range 65-77 µm. H) *Retiverrumonosulcites barmerensis* Tripathi, 1994; Size range 50-75 µm. I) *Clavadiporopollenites raneriensis* Ambwani and Singh, 1996; Size range 54-78 µm.**

The genus *Proxapertites* (Fig. 4A) is zonisulcate, having a long sulcus placed along the meridian of pollen. Such an organization of aperture causes an easy split of pollen into two more or less equal halves. Exine in these forms may be finely to coarsely reticulate.

The genus *Retiverrumonosulcites* (Fig. 4H) is spherical to oval in shape, 45-58 μm in size and possesses a small sulcus. The sulcal margins are thickened. Exine is microreticulate and is provided with clavae or verrucae of varying size. Verrucae are 2-5 μm in diameter whereas, the clavae are 7-20 μm long and 5-10 μm in diameter at the distal part. Morphological features of this genus strongly suggest that these pollen grains may also belong to plants of the family Arecaceae. *Clavadiporopollenites* (Fig. 4I) is diporate with a whorl of clavae at each pore. Other common forms in the Barmer assemblage, assigned to different species of *Acanthotricolpites* (Fig. 4D) are triporate, spinulate and, in all probability, are also related to the family Arecaceae. A complete list of the recorded palynotaxa and their abundances are given in Tables 1 and 2, respectively.

TABLE 1 **Palynotaxa from the Akli Formation, Barmer Basin.**

Pteridophyte spores
Lygodiumsporites eocenicus Dutta and Sah, 1970
Lygodiumsporites lakiensis Sah and Kar, 1969
Todisporites kutchensis Sah and Kar, 1969
Dandotiaspora dilata (Mathur) Sah, Kar and Singh, 1971
Dandotiaspora telonata Sah, Kar and Singh, 1971
Lycopodiumsporites palaeocenicus Dutta and Sah, 1970
Foveotriletes pachyexinous Dutta and Sah, 1970
Angiosperm pollen
Arecipites bellus Sah and Kar, 1970
Palmidites plicatus Singh in Sah and Singh, 1974
Palmidites naviculus Kar and saxena, 1981
Palmaepollenites eocenicus (Biswas) Sah and Dutta, 1966
Palmaepollenites kutchensis Venkatachala and Kar, 1969
Palmaepollenites nadhamunii Venkatachale and Kar, 1969
Palmaepollenites ovatus Venkatachala and Kar, 1969
Proxapertites assamicus (Sah and Dutta) Singh, 1975
Proxapertites crusus Hoeken-Klinkenberg, 1966
Proxapertites microreticulatus Jain, Kar and Sah, 1973
Kapurdipollenites baculatus Tripathi, 1994
Kapurdipollenites gemmatus Tripathi, 1994
Retiverrumonosulcites barmerensis Tripathi, 1994
Clavadiporopollenites raneriensis Ambwani and Singh, 1996
Acanthotricolpites bulbospinosus Singh and Misra, 1991
Acanthotricolpites kutchensis (Venkatachala and Kar) Singh and Misra, 1991
Acanthotricolpites complexus Singh and Misra, 1991
Tricolpites baculatus Kar and Jain, 1981
Grevilloideaepites eocenica Biswas emend. Singh and Misra, 1991
Ocimumpollenites indicus Kar, 1996
Kielmeyerapollenites eocenicus Sah and Kar, 1974
Spinizonocolpites echinatus Muller, 1968
Spinizonocolpites baculatus Muller, 1968
Spinizonocolpites prominatus (McIntyre) Sover and Evans, 1972
Spinizonocolpites adamanteus Frederiksen, 1994
Retimonosulcites ovatus (Sah and Kar) Kar, 1985
Matanomadhiasulcites maximus (Saxena) Kar, 1985
Matanomadhiasulcites microreticulatus (Datta and Sah) Kar & Kumar, 1986
Incrotonipollis burdwanensis (Baksi et al.) Jensonius and Hills, 1981

Palynozones based on quantitative analysis

The distribution and abundance of palynotaxa (Tables 1 and 2) show that the studied succession can be split into two biozones. The lower palynozone is characterized by a great abundance of pteridophytic spores and dinoflagellate cysts, whereas the upper palynozone is distinctly dominated by angiosperm pollen grains including palms and taxa that characterize coastal environments.

Lower palynozone

The succession of this zone consists mainly of shales and bentonites with a few lignite layers, with a total thickness of about 17 m. The major taxa in this palynozone are *Lygodiumsporites eocenicus*, *Todisporites kutchensis* and *Dandotiaspora dilata*. Other less abundant but significant forms of this zone are *Proxaperitites cursus* and *Retiverrumonosulcites barmerensis*. Marine dinoflagellate cysts from samples of this interval are *Apectodinium parvum, A. quinquelatum*, *Muratodinium fimbriatum* and *Cribroperidinium* sp.

Upper palynozone

The succession where this palynozone occurs is made up by bentonites, shales and lignite layers with a total thickness of 15 m (Fig. 3). Abundant palynotaxa in this palynozone are *Spinizonocolpites echinatus, Matanomadhiasulcites microreticulatus, Proxaperites cursus, P. microreticulatus, Kapurdipollenites gemmatus and Retiverrumonosulcites barmerensis*. Less widespread taxa are *Clavadiporopollenites raneriensis, Acanthotricolpites bulbospinosus, A. kutchensis, A. complexus, Tricolpites baculatus* and *Grevilloideaepites eocenicus*.

Comparison with other Early Palaeogene palynological assemblages

The Akli palynological assemblage is closely comparable with others recorded from Palaeocene-Eocene sequences of Rajasthan (Tripathi, 1994, 1995, 1997; Kar and Sharma, 2001), Kutch (Kar 1978, 1985; Saxena, 1981) and the Indus Coal Region in Pakistan (Frederiksen, 1994). Location of these localities is shown in Figure 1.

TABLE 2 **Abundance of palynotaxa in selected samples from the Akli Formation (▲ ≤ 10%; ★ 11-20%; ✦ 21-30%). See stratigraphic location of samples in Fig. 3.**

Affinity	TAXA	SAMPLE NUMBER											
		1	4	7	9	12	16	20	24	28	32	35	38
Lycopodiaceae	*Lygodiumsporites eocenicus*	▲		▲									
	Lygodiumsporites lakiensis					▲							
Osmundaceae	*Todisporites kutchensis*			▲				▲	▲				
	Dandotiaspora dilata	▲	★	★	▲	▲	▲	▲					
Matoniaceae	*Dandotiaspora telonata*	▲		▲	▲								
Lycopodiaceae	*Foveotriletes pachyexinous*				▲	▲							
	Arecipites bellus									▲			
	Palmidites plicatus								▲	▲	▲		
Arecaceae	*Palmidites naviculus*								▲	▲	▲	▲	
	Palmidites ovatus								▲	▲	▲		▲
	Palmidites Kutchensis								▲		▲	▲	
	Spinizonocolpites echinatus								▲		▲	▲	
	Spinizonocolpites baculatus								▲			▲	▲
	Spinizonocolpites prominatus								▲		▲	▲	
Arecaceae	*Spinizonocolpites adamanteus*								▲	▲		▲	
Liliaceae	*Retimonosulcites ovatus*											▲	
	Matanomadhiasulcites maximus										▲	▲	
	M. microreticulatus										▲	▲	
	Proxapertites assamicus									▲	▲		
Arecaceae	*Proxapertites microreticulatus*									▲	▲	✦	
	Kapurdipollenites baculatus									✦	▲	✦	
Arecaceae	*Kapurdipollenites gemmatus*									✦	▲	★	
Arecaceae	*Retiverrumonosulcites barmerensis*									★	★	★	
Arecaceae	*Clavadiporopollenites raneriensis*									★	▲	▲	
	Acanthotricolpites bulbospinosus									▲	▲	▲	▲
	Acanthotricolpites kutchensis									★	▲	▲	
Arecaceae	*Acanthotricolpites complexus*									▲	▲		
Unknown	*Tricolpites baculatus*										▲		
Onagraceae	*Grevilloidaepites eocenicus*									▲	▲		
	Fungal remain										★	★	
	Dinoflagellate cysts			★	▲	▲	▲						

Rajasthan palynological assemblages

The palynological assemblages described from Upper Palaeocene-Lower Eocene samples of bore-holes drilled near Jalipa and Kapurdi in the same Barmer District of Rajasthan (Tripathi, 1994, 1995) are very similar to the Akli Fm assemblage and share with it different species of *Kapurdipollenites, Retiverrumonosulcites, Acanthotricolpites* and *Spinizonocolpites*. In addition, the Zone A palynoassemblages described from the subsurface Upper Palaeocene sequences of other two bore-holes (MK 327 and MK 332) drilled near Kapurdi (Tripathi, 1997) also resemble closely the Akli assemblage. *Dandotiaspora dilata, Dandotiaspora telonata, Proxaperites assamicus, Proxapertites microreticulatus, Palmidites plicatus, Palmidites naviculus, Spinizonocolpites echinatus, Retimonosulcities ovatus* and *Matanomadhiasulcites maximus* are palynotaxa recorded in both assemblages.

The Akli Fm palynological assemblage is also comparable with that described by Kar and Sharma (2001) from the Upper Palaeocene part of bore-hole BH-125 drilled near Bithnok (Bikaner, Rajasthan), as both show the occurrence of *Dandotiaspora dilata, Proxapertites cursus, Spinizonocolpites baculatus and Ocimumpollenites indicus*. However, the abundance of Arecaceous pollen (such as *Kapurdipollenites baculatus, K. gemmatus* and *Retiverrumonosulcites barmerensis*) in the Akli assemblage is a distinctive feature from the Bithnok bore-hole palynoassemblage.

The Kutch palynoflora

The similarities between the new studied assemblage and that from Matanomadh Formation in Kutch are noteworthy. Common morphotypes found between the *Dandotiaspora dilata* and *Neocouperipollis brevispinosus* Cenozones (defined by Saxena, 1981) that are shared by both the Matanomadh and Akli assemblage include *Dandotiaspora dilata*, *D. telonata, Lygodiumsporites eocenicus, L. lakiensis, Palmaepollenites eocenicus, P. kutchensis* and *P.* n*adhamunii*. In addition, two species of *Acanthotricolpites*, namely *A. bulbospinosus* and *A. kutchensis (Couperipollis kutchensis*), described from the subsurface paleogene successions of Kutch (Venkatachala and Kar, 1969) are also abundant in the Akli assemblage. However, some differences must also be stressed. Thus, there are several morphotypes that have been recorded from the aforementioned two Cenozones in the Matanomadh Formation but are absent in the Akli Formation (i.e., *Tricolpites minutus, Trilatiporites, Sonneratiopollis and Lakiapollis*. On the contrary, the Akli assemblage contains abundant *Spinizonocolpites,* a pollen which is absent in the assemblage of the Matanomadh Formation.

The palynoflora of the Indus Region (Pakistan)

The Upper Palaeocene assemblage of core samples from the Lower Indus coal region of Pakistan (Frederiksen, 1994) resembles the present assemblage in the common occurrence of species of *Spinizonocolpites*, *Proxopertites cursus* and *Matanomadhiasulcites maximus*.

Chronostratigraphy of the studied sequences

Indian Palaeocene deposits are characterized by relatively great abundances of different species of *Dandotiaspora, Lycopodiumsporites*, *Neocouperipollis, Proxapertites, Spinizonocolpites*, *Palmidites* and *Kielmeyerapo-llenites* (Singh, 1977; Saxena, 1980, 1988; Tripathi and Singh, 1984; Kar, 1985; Kar and Kumar, 1986; Tripathi, 1995, 1997; Kar and Sharma, 2001). In the Eocene these forms either dwindle or disappear, other palynofossils becoming dominant (Kar, 1992). Age determination and distinction of Palaeocene and Eocene sediments based on ranges of palynotaxa alone is therefore rather difficult. However, a few attempts have so far been made in the Rajasthan Basin (Singh and Dogra, 1988; Tripathi, 1997).

Earlier palynological studies from bore-holes drilled near Kapurdi and Jalipa already suggested the occurrence of Palaeocene and Eocene deposits in the Barmer District (Tripathi, 1995, 1997). Lignites from these bore-holes that were dated as Late Palaeocene yielded different species of *Dandotiaspora, Lycopodiumsporites, Matanomadhiasulcites*, *Proxapertites, Spinizonocolpites*, and *Palmidites*. In fact, a great abundance of this pollen characterizes the Late Palaeocene (Kar, 1996, Tripathi, 1997). In the Akli Fm different species of *Dandotiaspora, Proxapertites*, *Spinzonocolpites* and *Matanomadhiasulcites* are also widespread.

Singh and Dogra (1988) identified five zones in the Palaeocene to Lower Eocene deposits of the Bikaner Basin. The lower SP-1 and SP-2 zones represent the Early Palaeocene, SP-3 and SP-4 zones correspond to the Late Palaeocene and SP-5 zone characterize the Early Eocene. Since many palynotaxa typical of SP-3 and SP-4 zones have been identified in the studied Akli succession, such as *Dandotiaspora dilata*, *Lygodiumsporites lakiensis, Proxapertites cursus*, *Kielmeyerapollenites eocenicus* and *Palmidites plicatus*, a Late Palaeocene age is quite probable. This age would be confirmed by the dinoflagellate taxa recorded in the lower part of the Akli Fm, which are also indicative of a Late Palaeocene to Earliest Eocene age (Garg et al., 1995; Garg and Khowaja Ateequzzaman, 2000). Therefore, taking into account the available information, the Akli Fm succession is Thanetian to Ypresian in age.

PALYNOFACIES ANALYSIS

The palynofacies analysis was carried out considering the abundance and distribution in each sample of different types of organic matter, such as structured terrestrial (leaf cuticle, woody particles), palynofossils, degraded phytoclasts (biodegraded terrestrial, amorphous and pyritized amorphous organic matter) and oxidized plant fragments (black debris). This analysis was based on the compositional characteristics and the quantitative assessment of the dispersed organic matter. For quantitative analyses three hundred plant derived organic particles were counted in each sample. The abundance of each component was determined and expressed in a curve diagram (Figs. 3 and 5).

The lowermost part of the grey shale unit, which overlies the basal shale bed with siderite nodules and burrows, is highly siliceous and devoid of plant microfossils. However, most samples from this unit proved suitable for palynofacies analyses. The relative abundance of structured terrestrial palynodebris, such as leaf cuticle and woody tissues, decreases upwards from 40 to 12%. Biodegraded terrestrial contents vary between 20 and 40%. Amorphous matter content gradually increases upwards from 6 to 40%. Black debris ranges from 10 to 12%, whereas the relative abundance of spore pollen is about 2-4%.

All lignite seams show almost uniform distribution patterns of various types of organic matter, though some variation in the relative abundance of amorphous and black debris is noticeable. The relative abundance of biodegraded phytoclasts (biodegraded terrestrial and amorphous organic matter) is higher in comparison to other lithotypes. Another remarkable feature observed in lignite beds is the occurrence of pyritized amorphous matter (Fig. 3).

The clay beds intercalated between lignite seams contain rich structured terrestrial (10-35%) and biodegraded terrestrial (up to 50-65%) organic matter. The relative abundance of black debris is higher than in the underlying

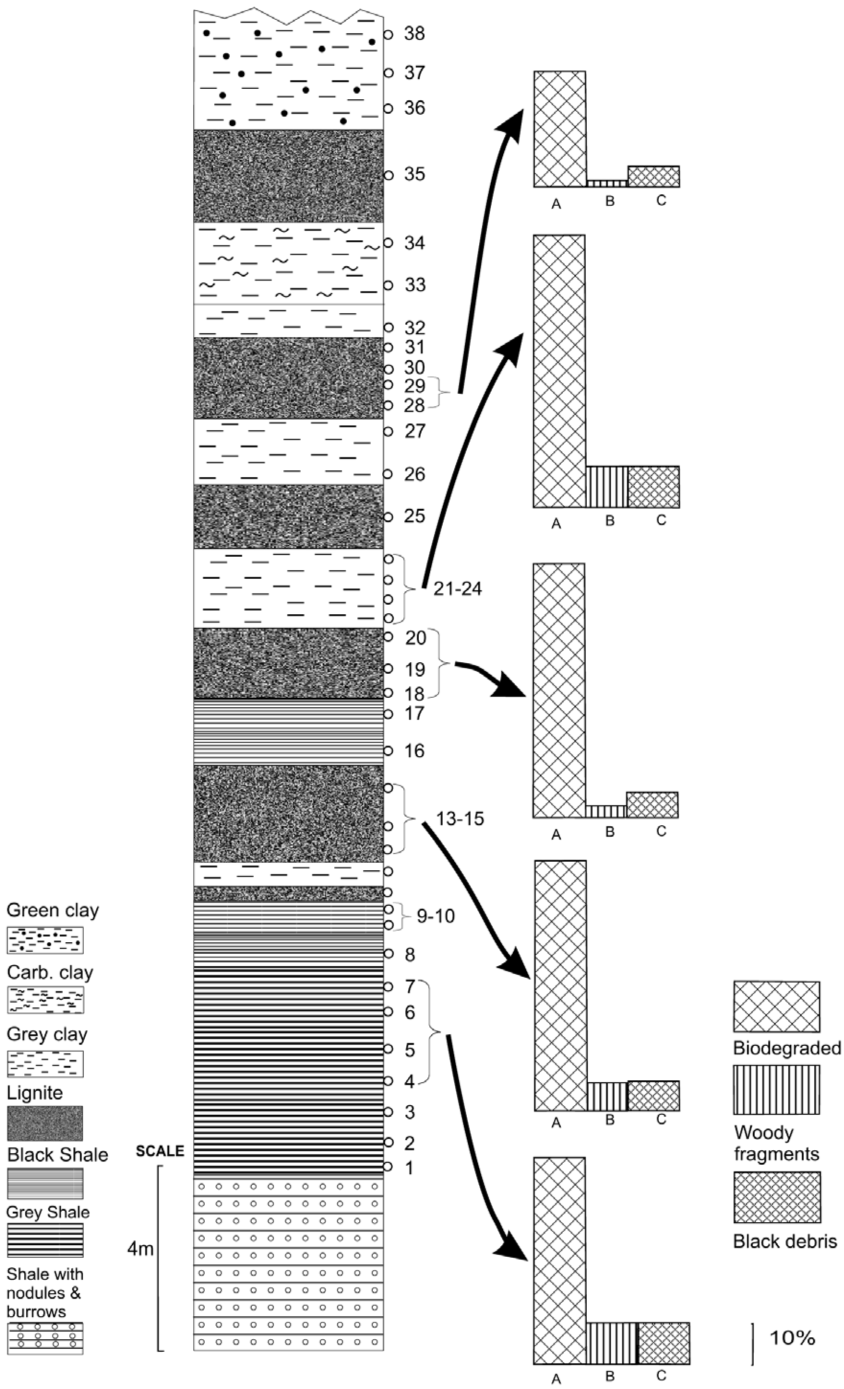

FIGURE 5 | **Organic matter characterizations in distinctive facies of the Akli Formation.**

sequences. Pyritized amorphous organic matter does not occur in the clay beds.

Depositional environment

Previous sedimentological studies suggested that the Akli Formation record sedimentation on a floodplain which underwent marine incursions (Sisodia and Singh, 2000). These conclusions were mainly drawn on the basis of the inferred channel fill sedimentation and fining upward nature of each lignite cycle in the Akli Formation. The dominant bentonitic claystones represent low-energy shallow-water conditions, whereas occasional thin sandstone beds and siltstone within claystone show that the area was periodically affected by flood events. Further details can be gained now by means of the palynological assemblages.

The occurrence of both terrestrial organic matter and dinoflagellate cysts in some black shales and grey clay beds (sample nºs 7, 9, 12, and 16) certainly suggests proximity to the palaeo-shoreline (Habib et al. 1994). Furthermore, the occurrence of different species of *Proxapertites*, *Palmaepollenites*, *Palmidites* and *Arecipites bellus* in the assemblage clearly indicates coastal environments.

The elements of the Akli palynoflora that have been ascribed to different species of *Spinizonocolpites* show a great affinity with the extant *Nypa*. Similarly, *Proxapertites*, on the base of its morphological features, has been interpreted to represent an extinct group of palms possibly related to *Nypa* (Muller, 1968). The genus *Acanthotricolpites*, in all likelihood also related to *Nypa* (Venkatachala et al., 1986) is also profusely recorded in the Akli assemblage. The high diversity of *Nypa*-like pollen is also a common feature elsewhere, as the fossil record shows that different species of this genus produced pollen with a great morphological diversity (Kar, 1985; Kar and Kumar, 1986; Frederiksen, 1994; Tripathi, 1994; Tripathi et al., 2003; Scafati et al., this issue). The genus *Nypa*, represented by one extant species (*N. fruticans*), is a mangrove palm growing in tidal mud flats fringing the tidal reaches of large fresh water rivers (Morley, 2000). Therefore, all the aforementioned types of *Nypa*-like pollen proved very useful to interpret the Akli sedimentary environment, as this genus is known to have low pollen productivity (Muller, 1964; Frederiksen, 1985) and its occurrence, even in low abundance, indicates a good representation of this genus at the time of sediment accumulation. Chaloner (1968) further suggested that large *Nypa* pollen cannot be transported long distances towards the sea from the mangrove environment. Therefore, the great abundance of *Nypa* and *Nypa*-like pollen, along with the large-size of the *Nypa*-like pollen, suggest that accumulation of the Akli sediments took place in a coastal swamp fringed by thick mangrove vegetation chiefly constituted by *Nypa*. It can also be inferred that Pteridophytic spores and other angiospermic elements in the assemblage were transported to the site of deposition through river channels. Following the same line of reasoning, existence of mangrove forests at the beginning of Eocene in some basins of Tasmania was also inferred by Pole (1998) and Pole and Macphail (1996) on the basis of abundant occurrences of *Spinizonocolpites prominatus*. Pollen of *Proxapertites* and *Nypa* has also been recorded in deltaic and shallow marine sediments (Muller, 1979; Mandal, 1986; Kar and Kumar, 1986; Tripathi, 1997; Kar and Sharma, 2001).

It is concluded that the Akli Formation was deposited in a palaeoshoreline with extensive swamps fringed by abundant mangrove *Nypa* palms, where large amounts of detritus were derived from adjacent areas. The neighbouring areas were inhabited by vegetation chiefly dominated by Arecaceae, Liliaceae, Oleaceae, Guttiferae, Lamiaceae and Onagraceae. Prevalence of fragments of land plants and their transportation to the depositional site indicates the dominance of higher plants in the surrounding vegetation. Thus, the occurrence of resin lumps throughout the succession indicates the involvement of higher plant groups, mostly arboreal angiosperm trees that growth in lagoonal swampy areas (Masron and Pocock, 1981; Batten, 1996). The occurrence of dinoflagellate cysts in some black shale and grey clay beds readily indicates mixing with marine water near the shore, their low abundance being caused by the dilution of marine in origin elements due to the high influx of terrestrial components.

Palaeoclimate

Much of the very diversified flora that characterized the Indian subcontinent during the Palaeogene is still thriving today (Morley, 2000). The majority of the families represented in the Akli assemblage (Schizaeaceae, Arecaceae, Oleaceae, Lamiaceae and Guttiferae) are tropical to subtropical in their present-day distribution (Table 3). Other families (Osmundaceae, Matoniaceae, Lycopodiaceae, Lilaceae and Onagraceae) are cosmopolitan. Temperate elements are conspicuously absent in the Akli assemblage. *Proxapertites* and *Nypa* pollen both had a pantropical distribution too, and further suggest monsoonal conditions. Abundant pteridophytic spores and fungal elements also indicate a tropical flora, while the good representation of Microthyriaceous fungal fruiting bodies suggests warm and humid conditions with large precipitation.

This palaeoclimatic interpretation is fully coincident with the available palaeogeographic reconstructions (Parrish et al., 1982; Fig. 6), which suggest that at the beginning of the Tertiary India separated from Madagascar and

TABLE 3 | **Present-day distribution of families related to the palynotaxa found in the Akli Formation assemblage.**

Families	Palynotaxa	Present day distribution
Osmundaceae	*Todisporites kutchensis*	Cosmopolitan
Matoniaceae	*Dandotiaspora dilata, D. telonata*	Cosmopolitan
Lycopodiaceae	*Lycopodiumsporites palaeocenicus*	Cosmopolitan
	Foveotriletes pachyexinous	
Schizaeaceae	*Lygodiumsporites eocenicus, L. lakiensis*	Tropical- subtropical
Arecaceae	*Palmidites plicatus, P. naviculus*	Tropical- subtropical
	Palmaepollinites eocenicus, P. kutchensis	
	P. nadhamunii, Proxaperitites assamicus	
	P. cursus, P. microreticulatus	
	Spinizonocolpites baculatus, S. prominatus	
	S. adamenteus, S. echinatus	
	Kapurdipollenites baculatus, K. gemmatus	
	Arecipites bellus, Retiverrumonosulcites barmerensis	
Liliaceae	*Retimonosulcites ovatus*	Cosmopolitan
Oleaceae	*Tricolpites baculatus*	Mainly tropical
Guttiferae	*Kielmerapollenites eocenicus*	Tropical
Lamiaceae	*Ocimumpollenites indicus*	Tropical
Onagraceae	*Grevilloideaepites eocenica*	Cosmopolitan

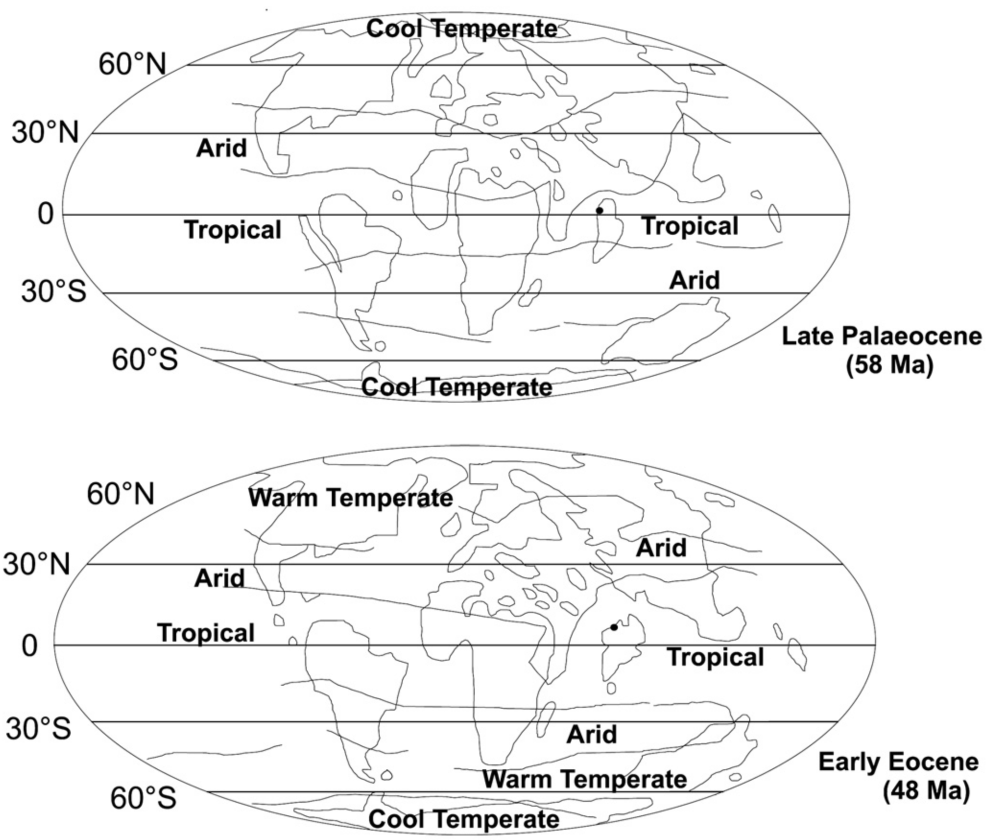

FIGURE 6 | **Palaeogeographic map showing the position of India and Rajasthan during Late Palaeocene and Early Eocene times and the location of the studied palynological record (after Parrish et al., 1982).**

started to drift in NNE direction. Such drift brought this subcontinent into a humid equatorial zone.

Diagenesis

The fine-grained composition of shales and lignites allowed the occurrence of well-preserved structured phytoclasts ranging in abundance from 3 to 10%. However, phytoclasts derived from clay and shale samples show better preserved morphological details than those recovered from lignite. In beds with fine lithologies compaction played a major role in the preservation of organic matter (Demaison and Moore, 1980).

Figure 5 shows quantitative data of palynodebris and of various organic matter types with respect to specific lithologies. On broad outline, the degree of organic matter degradation shows the intensity of microbial activity for different lithotypes. The abundance of biodegraded terrestrial and amorphous organic matter throughout the succession may be attributed to high microbial activity (both by fungi and bacteria) and overall anoxic burial conditions. Thus, lignite beds contain very abundant biodegraded amorphous and pyritized amorphous organic matter, which indicate prevalence of anoxic conditions after burial. Palynodebris content in the clayey beds is also characterized by large amounts of biodegraded and amorphous matter (50% in average). Structured and black debris (9% each in average) indicate moderate anoxic condition. The microbial action during diagenesis of clayey beds was comparatively less intense than that in the lower and middle lignite seams.

Both the relative lower abundance of biodegraded terrestrial and amorphous matter at the upper part of the succession, together with an increased amount of black debris, indicate the progressive prevalence of moderately oxic burial conditions. This was favored by an originally lower supply of organic detritus and by the comparatively coarser size of the sediment (Pittet and Gorin, 1997; Bambardiere and Gorin, 1998). This situation allowed structural phytoclasts to come into contact with air for longer periods, this fact resulting in oxidation and transformation of organic detritus into black-colored or opaque matter.

CONCLUSIONS

1. Range and abundance of palynotaxa and dinoflagellates in the studied assemblages suggest that the age of the Akli Formation is Thanetian to Ypresian.

2. Palynological assemblages from the Akli Formation are rich in angiospermic pollen, being dominated by forms that show affinity with *Nypa* mangrove.

3. The Akli assemblage is closely comparable to other Upper Palaeocene to Lower Eocene assemblages of western India. It also bears a strong resemblance to Upper Palaeocene assemblages from the Indus Coal region in Pakistan.

4. The studied assemblages indicate that the Akli Fm sequences were deposited in coastal floodplains with a mangrove dominated vegetation and that underwent frequent marine incursions.

5. The abundance of biodegraded terrestrial and amorphous organic matter throughout the sequence shows the dominance of anoxic conditions after burial of organic matter. The upwards increasing abundance of black debris shows a gradual change to moderately oxic burial conditions.

6. Grey shales contain well-preserved structured phytoclasts, whereas lignite beds bear large amounts of biodegraded amorphous and pyritized amorphous organic matter. Both components confirm the prevalence of anoxic conditions. Clay beds with greater abundance of biodegraded and amorphous organic matter indicate moderate anoxic conditions.

ACKNOWLEDGEMENTS

The authors are thankful to Dr. N.C. Mehrotra, Director of the Birbal Sahni Institute of Palaeobotany at Lucknow for his constant encouragement throughout this work. Efforts put in by the referees (M. Raigemborn and L.H. Scafati) and the editorial committee of Geologica Acta (A. Payros, V. Pujalte and C. Martin-Closas) is gratefully acknowledged, as the suggested modifications significantly helped in improving the paper.

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Manuscript received June 2007;
revision accepted February 2008;
published Online November 2008.