Palaeoecological and palaeoclimate potential of subsurface palynological data from the Late Quaternary sediments of South Kerala Sedimentary Basin, southwest India

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The accrued palynological data obtained from the subsurface sediments of South Kerala Sedimentary Basin have been found to be useful for identifying various ecological complexes and their environmental preferences. The occurrence and relative abundance of *Cullenia exarillata* pollen along with other wet evergreen forest members at certain intervals are of great significance as they indicate the prevalence of heavy rainfall during Early Holocene. This aspect is further complemented by the presence of a large number of fungal remains. In contrast, their scarcity and even absence at higher levels in boreholes point towards relatively dry climate during Late Holocene. Another significant aspect of the palynological record is the occurrence of reworked pollen of *Eugeissona* (Arecaceae) and *Ctenolophon* (Ctenolophonaceae) restricted to one or two intervals in the boreholes, as these forms are common in Miocene sediments of the Warkalli Formation. Increased organic matter in Late Quaternaries may be attributed to relatively higher rates of weathering and erosion of the hinterland as a result of enhanced SW monsoon during Late Pleistocene–Early Holocene. Diatoms and palynodebris, including non-pollen palynomorphs (NPP) observed in palynological preparations are also found to be important for interpretation of the Late Quaternary climate of southwest India.

Keywords: Late Quaternary sediments, palynoflora, palaeoclimate.

THE study of Quaternary geology and associated events is important, as the present-day landscape and environment are products of various processes, including climatic variations, sea-level changes and tectonics. The interaction of climate and geological processes results in significant ecological changes, documented in the sediments deposited during the concerned period. Since the Quaternary formations of Kerala coast have not received much attention despite being recognized and exploited for mineral deposits and freshwater needs of the rural households, there is a need to address the various aspects related to the geological processes and the associated events, including the environmental changes of the recent past. Although the Quaternary of the west coast of India in general has been addressed in detail, the southwestern part of Kerala has been in focus only recently[1–3]. The Quaternary sequence is better preserved in the South Kerala Sedimentary Basin (SKSB) along the west coast of India and it is estimated to be about 80–100 m thick. The Quaternaries overlie the well-known Tertiary Formation and are easily distinguishable as the laterite forms their base in most places (K. Najeeb, unpublished)[4–6].

The Quaternary sediments are best developed and found in the coastal plains of SKSB between 8°45′ and 10°15′ lat. It is the landward extension in the Kerala–Konkan Basin (KKB) in the southwestern part of India. Except broad generalities, precise dating of transgressive/regressive cycles, tectonics and geomorphic evolution of these Quaternary deposits are yet to be addressed comprehensively. As of now, there has not been any pollen data for understanding the vegetational history and palaeoenvironment from this region, although attempts were made in the past to reconstruct the palaeoclimate for south and southwestern India based on off-shore data[7,8] and for the Nilgiris using peat deposits[9–12]. In fact, pollen analyses in southwest India have been mainly restricted to the Neogene sediments[13–15]. Nevertheless, these data have relevance to palaeoclimatic and phytogeographic considerations, while dealing with the Quaternary deposits of Kerala. Systematic geological and geomorphological studies of the SKSB were taken up for the first time during 1998–2003, with a view to build up the Quaternary stratigraphy and associated geological events[1,16]. Palynological and palynodebris data (organic remains of nonconventional palynomorphs, including non-pollen polynomorphs (NPP)) obtained from the subsurface sediments of some of the wells representing the Late Pleistocene–Holocene period are being addressed in this communication with reference to palaeoecology and palaeoclimate of the SKSB.

The geology of Kerala is dominated by the Pre-Cambrian crystalline rocks and intrusives therein. Sedimentary rocks found along the coast are best developed in the SKSB. They are composed of Vaikom, Quilon and Warkalli formations (Early Miocene–Middle Miocene) overlain by the Quaternary sediments. Laterite capping is found on the Tertiary sediments and basement rocks. Laterite is found to separate the Tertiary formations from the Quaternary sediments in a large part of the SKSB, thus acting as a useful lithostratigraphic constrain in the sedimentary column. The deposition of Quaternary sediments has been essentially influenced by the structural pattern inherited from the Tertiary, with modifications. The study area (Figure 1) falls within the geographical limits of the Alappuzha, Kottayam, Pathanamthitta, Ernakulam and Kollam districts in the southern part of the Kerala Qua-

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Table 1. Stratigraphic sequence of Kerala (modified after K. Najeeb Mohammed, unpublished)

Quaternary	Vembanad Formation	Sands, clays, molluscan shell beds, riverine, alluvium and floodplain deposits. Laterite capping the crystallines and Tertiary sediments.
	Warkalli Formation	Sandstone and clay with lignite seams.
Tertiary	Quilon Formation	Limestone marls, clays/calcareous clays with marine fossils.
	Vaikom Formation	Sandstones with pebbles and gravel beds, clays and lignite and carbonaceous clay.
Mesozoic to Archaean		Intrusives: Veins of quartz, pegmatites, granites, granophyres, dolerite and gabbro. Garnet sillimanite gneiss, hornblende–biotite gneiss, garnet–biotite gneiss, quartzo–feldspathic gneiss, charnockites, charnockite gneiss, etc.

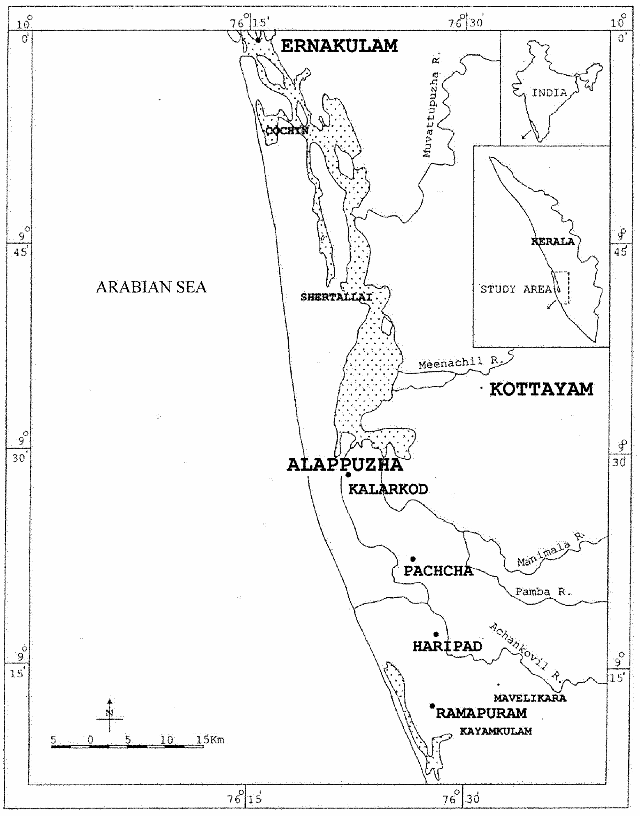

Figure 1. Location of borehole in South Kerala Sedimentary Basin.

ternary Basin (KQB) and belongs to a small part of the KKB. A generalized geological cross-section along the coast in the SKSB is given in Figure 2. The basin along the coast can be divided into a Southern Block (SB), Central Depression (CD) and Northern Block (NB). In the E–W direction, the basin is divisible into an Eastern Flank (EF) and a Western Depression (WD).

Subsurface data obtained from two boreholes, viz. Ernakulam and Pachcha have been used to reconstruct the lithology, sedimentary features and for pollen analysis (Figure 3). The Quaternary sediments have been earlier assigned to the Vembanad Formation[17] and the same is adopted herein too. The generalized stratigraphic relationship of the SKSB is given in Table 1. Details of the Quaternary stratigraphy, regional tectonics, depositional environment and palaeoclimate based on all the borehole data are dealt with separately.

The area encompassing the SKSB has a warm, humid tropical climate with an oppressive summer and abundant rainfall during the SW monsoon. Average surface temperature during the pre-monsoon season is around 32°C. The hot summer from March to May is followed by the SW monsoon from June to September. With the onset of the SW monsoon in June, the temperature gradually decreases and comes down to an average of 28°C. October and November form the post-monsoon season followed by the NE monsoon in December. The monsoon climate is generated along the SW coast of India due to the seasonal reversal of wind circulation in the Arabian Sea. Nearly 60% of the annual rainfall comes from the SW monsoon and an average of about 300 cm rainfall is received. Seasonal changes brought about by the monsoon and the short-term changes induced by the tides, considered to be the main factors influencing the hydrology of the lowlands and the associated wetlands, which in turn sustain the vegetation types in these zones. In general, rainfall shows an increasing trend from coastal to middle part and then subsequently decreases. This differential rainfall trend and the topography of the terrain have an impact on the distribution of plants and the vegetation types along the west coast of southwestern India.

The main source of organic matter in the SKSB is from the vegetation of the nearby southern districts belonging to the lowlands, midlands and dense forests of the Western Ghats. The heavy rainfall combined with moderate temperature and fertile soil support abundant vegetation. The indigenous vegetation of both coastal and midlands substantiates the fact that the entire area was undoubtedly tropical wet evergreen forest, as seen in the sacred groves and mangrove forests, with all gradations between the two. This is further supported by the fossils and coral reefs excavated from the coastal region. This vegetation has, of late, undergone considerable change due to geologic processes, ecological shift and developmental activities. However, relics of natural vegetation are still preserved throughout the state in all the three major zones.

The two major characteristic types of vegetation of the lowlands and coastal zone are strand and estuarine. The

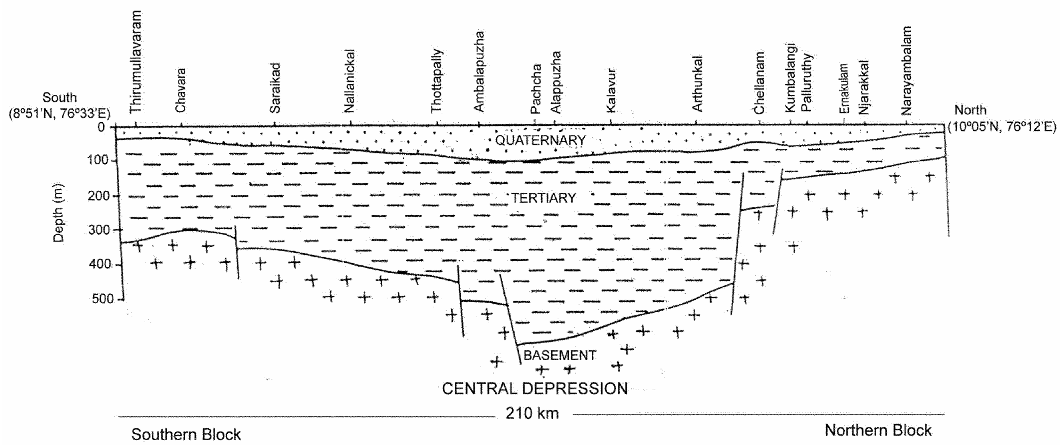

Figure 2. Geological cross-section along the coast in South Kerala Sedimentary Basin (modified after Kumaran *et al.*[29]).

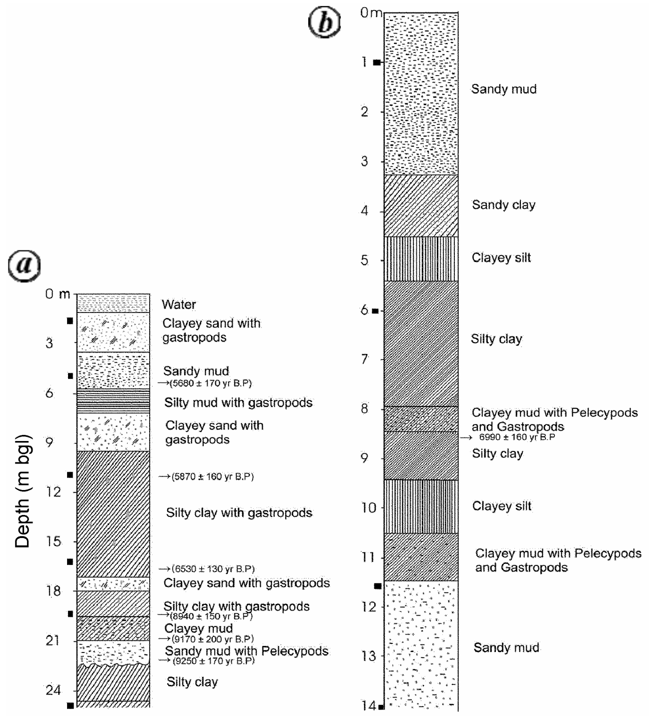

Figure 3. Lithological sequence in (***a***) Ernakulam and (***b***) Pachcha boreholes of South Kerala Sedimentary Basin.

former is characterized by open mat-forming pioneers in varying proportions followed by herbs, shrubs and trees distributed on a relief beyond the high tide limit. Winds and waves are the two main interacting factors in the formation of this habitat. An outer open pioneer zone, a closed herbaceous zone following it, a middle mixed bushy zone and an inner woodland zone can be distinguished in the coastal zone. The outer zone is dominated by sand binders and the common species are *Cyperus arenarius*, *Fimbristylis cymosa*, *Heliotropium marifolium*, *Ipomoea pes-capre*, *Launaea sarmentosa*, *Mollugo cerviana* and *Spinifex littoreus*. Common plants of the bushy zone are *Calotropis gigantea*, *Capparis brevispina*, *Cassia auriculata*, *Sida cordifolia*, *Tephrosia hirta*, *T. maxima*, *Turnera angustifolia* and *Vitex trifolia*. The inner woodland has *Calophyllum inophyllum*, *Derris indica*, *Morinda citrifolia*, *Thespesia populnea* and *Wrightia arborea*. *Anacardium occidentale*, *Casuarina litorea* and *Cocos nucifera* are the more important cultivated trees besides the recently introduced species of *Acacia*. Although typical estuarine vegetation is not found, the backwaters along the coast support highly salt-tolerant species. The margins of these marshes are abundant with thickets of *Acanthus ilicifolius* and *Acrostichum aureum*. The common trees in this habitat are *Aegiceras corniculatus*, *Avicennia marina*, *A. officinalis*, *Barringtonia racemosa*, *Bruguiera conjugata*, *B. gymnorrhiza*, *Carallia brachiata*, *Lumnitzera racemosa*, *Rhizophora apiculata*, *Scaevola sericea* and *Sonneratia caseolaris*.

The midlands have a few patches of forests, which are the remnants of moist deciduous and evergreen forests of the past, besides crops like coconut, arecanut, cashew, rice, tapioca, pepper and cocoa. The prominent trees found in the midland area are *Albizia chinensis*, *A. odoratissima*, *Alstonia scholaris*, *Artocarpus hirsutus*, *Bridelia retusa*, *Clerodendron infortunatum*, *Macaranga peltata*, *Mallotus philippensis*, *Terminalia crenulata*, *T. paniculata* and *W. arborea*. The midlands also have a large number of sacred groves which remained immune from human interference on religious grounds, and they are confined to lower elevations. They harbour a number on wild species of the Western Ghats and *Aglaia elaeagnoidea*, *Aporusa lindleyana*, *Buchanania axillaris*, *B. lanceolata*, *C. inophyllum*, *Caryota urens*, *Cinnamomum malabatrum*, *Diospyros candolleana*. *D. malabarica*, *Ficus exasperata*, *F. religiosa*, *Holigarna arnottiana*, *Hydnocarpus pentandra*, *Litsea glutinosa*, *Mangifera indica*, *Mimusops elengi*, *Olea dioica*, *Sterculia foetida*, *S. urens*, *Strychnos nux-vomica*, *Syzygium cuminii* and *S. travanco-*

ricum. Smaller trees, shrubs, lianas, climbers, epiphytes and herbs make up the lower storey of the forest patches. Vegetation of the wetlands includes submerged aquatic, free-floating, rooted and semi-aquatic and moisture-loving plants, which are conspicuously seen in the midlands dominated by the river system.

The vegetation of the highlands is essentially that of the southern Western Ghats. The west coast tropical evergreen forest is found in valleys at high altitudes between 200 and 1500 m. *Cullenia–Mesua–Palaquium* is the major association here. Other important species are *Bischofia javanica*, *Dipterocarpus indicus*, *Drypetes* spp., *Hopea parviflora*, *Lophopetalum wightianum*, *Mesua ferrea*, *Syzygium* spp. and *Vateria indica*. Pollen representation of a few modern analogues, viz. *Agrostistachys meeboldii*, *Croton* spp., *Fahrenheitia zeylanica*, both in marine and non-marine of the Quaternary sediments, is also a significant part of the highland tropical evergreen forests[18].

The SKSB is under the cover of water bodies, wetlands and alluvium. Accordingly, samples for analysis were obtained through boreholes. Figure 1 gives the location of sites in the SKSB. The Ernakulam borehole is located on the NB. This 25 m long core was collected from the Vembanad Lake Basin at a location (9°59′29″N and 76°16′15″E) between Fort Kochi and Bolgatty Island. The Pachcha (near Alappuzha) borehole is located on the EF and the 14 m long core reveals an assemblage of highly varied textural categories. The samples analysed for pollen data obtained from the above selected intervals (Figure 3) were subjected to textural and palynological studies following standard procedures. The method suggested by Picard[19] was used for deciphering the sediment types, while palynodebris analysis was based on the method of Pocock *et al.*[20]. Radiocarbon (^{14}C) of a few samples of molluscan shells, and carbonaceous sediments were obtained from the Radiocarbon Laboratory, Birbal Sahni Institute of Palaeobotany, Lucknow. Results of radiocarbon analysis are given in Table 2.

The subsurface sediments encountered in Pachcha, Ernakulam, Haripad, Ramapuram and Kalarkodu boreholes in the SKSB were studied for palynofossils, diatoms and palynodebris analysis. The results of only two boreholes (Pachcha and Ernakulam) are dealt with here for sedimentology, palynology and depositional environments (Figure 4 *a* and *b*). Various ecological groups have been identified on the basis of their environmental preferences. A checklist of identified diatoms, spores, pollen and other organic forms are given in Table 3, and a few pollen–spore and other microfossils are illustrated in Figures 5–7. Palynological contents in almost all the boreholes are more or less the same, except for their relative abundance in certain intervals (Table 4). The organic remains other than pollen and spores have been collectively assigned to palynodebris, to appraise their ecological and palaeoclimate potential.

Table 2. Radiocarbon dates of borehole samples from Ernakulam and Pachcha

Location	Depth (m)	Sample type	^{14}C yrs BP
Ernakulam	20.2–20.3	Sediment	9250 ± 170
Ernakulam	19.4–19.5	Sediment	9170 ± 200
Ernakulam	17.9–18.0	Sediment	8940 ± 150
Ernakulam	15.7–15.8	Sediment	6530 ± 130
Ernakulam	10.0–10.1	Sediment	5870 ± 160
Ernakulam	3.8–3.9	Sediment	5680 ± 170
Pachcha	8.50	Shell	6990 ± 160

The most important aspect of palynological analysis has been its utility in interpreting the palaeoclimate of the Holocene in the SKSB. The fairly abundant occurrence of *Cullenia exarillata* (Bombacaceae) pollen at certain intervals of various boreholes is significant, particularly while inferring climatic conditions such as heavy rainfall and wet period. Being a member of the wet evergreen forest and enjoying a high precipitation range (>3000–5000 mm), the occurrence and relative abundance of *Cullenia* pollen in the marine, marine–brackish–lagoonal facies indicate a heavy rainfall. As this plant grows far from the sea coast and is presently restricted to relatively higher altitudes, these pollen grains must have been transported and eventually deposited into lagoons. The intervals of 5–10 m in Pachcha, 8–17.5 m in Ernakulam, at 10.85 m in Ramapuram, 27.25–30.0 m in Kalarkodu well and 12.00–17.00 m depth in Haripad are considerably important in this aspect. In fact, the radiocarbon dates of a few samples of these intervals fall within the period 10–4 ky BP of increased monsoon over the Indian subcontinent (Table 2)[12,21–23]. Further, pollen grains of other wet evergreen forest members (*F. zeylanica*, *Agrostistachys meeboldii* (Euphorbiaceae) and *Lophopetalum wightianum* (Celastraceae)) have been recovered along with *C. exarillata*. Accordingly, the presence of these inland/montane plant taxa to the Arborescent Plant (AP) of C3 vegetation in the marine sequences is of great significance, indicating improved monsoon during the Early Holocene. The 17.9–18.0 m level in the Ernakulam profile (Figure 4 *a*) shows dominance of Arecaceae, Liliaceae and Euphorbiaceae pollen. Abundance of *Pandanus*, *C. exarillata*, Cyanobacteria and fungal complex from this level onwards suggests increased atmospheric pressure and wet period. The low frequency of foraminiferal linings infers reduced marine conditions around this period. A reverse trend, i.e. an aridity situation has been accounted for at 3 m depth level in Pachcha, probably towards the later part of the Holocene, where recovery of organic matter is poor. At 3 m interval there is decrease of *C. exarillata* and Liliaceae pollen. However, the occurrence of *Botryococcus* marks the dry period from this level. Terrestrial palynodebris (cuticles, tracheids, etc.) is scarce and in fact, no representation of AP of C3 vegetation has

Table 3. Palynological and diatom related ecological complexes and a checklist of taxa from subsurface sediments (boreholes) of SKSB

Marine diatoms	Dinoflagellates	Other marine forms	Mangroves and mangrove associates	Brackish water/ littoral	Freshwater
Actinocyclus ehrenbergii *Actinocyclus ingens* *Actinocyclus ellipticus* *Auliscus punctatus* *Bacteriastrum* spp. *Biddulphia aurita* *Campylodiscus clevei* *Coscinodiscus excentricus* *Coscinodiscus asteromphalus* *Coscinodiscus radiatus* *Coscinodiscus nodulifer* *Cyclotella striata* *Cymbella* sp. *Navicula spectabilis* *Melosira sulcata* *Navicula* sp. *Pleurosigma angulatum* *Surirella ovata* *Surirella* sp. *Thalassiosira oestrupii* *Triceratium cinnamomeum* *Triceratium favus*	Acritarchs (simple and with ornamentation) *Amiculosphaera umbracula* *Eatonocysta ursulae* *Batiacasphaera micropapillata* *Hystrichosphaeropsis obscura* *Impagidinium patulum* *Lejeunecysta* spp. (= *Peridinium* spp.) *Melitasphaeridium* sp. *Polysphaeridium zoharyi* *Spiniferites elongatus* *Spiniferites membranaceus* *Spiniferites pseudofurcatus* *Spiniferites splendidus* *Selenopemphix nephroides* *Selenopemphix selenoides* *Multispinula quanta* *Oligosphaeridium complex* *Tuberculodinium vancampoae*	Foraminiferal linings (microforaminifera), Scolecodonts (polychaete worm jaws), *Bacteriastrum* sp., Sponge spicules	*E. agallocha* (Euphorbiaceae), Rhizophoraceae, Malvaceae (*Thespesia* sp.), Salt glands of various types (*Heliospermopsis* sp. common) Cuticles with salt glands *Cirrenalia* sp. (fungal spore)	*Rivularia* sp. and *Gleotrichia* sp. (colonies, filaments of blue green alga), *Chara* sp. (gyrogonites of lacustrine green alga), *Acrostichum aureum* (fern), *Rhabdocoela* cocoon, *Turbellaria* cocoon, Rotifers	*Botryococcus* sp. (green alga), *Pediastrum* sp. Nostoc colony, *Potamogeton* sp. (rugulate, monocolate pollen), Liliaceae, aquatic flowering forms represented by pollen. Aquatic insects (chironomids, mites and midges), Thecamoeba

Freshwater– flood plain	Fungal complex	Shoreline plant complex	Fern complex	Inland plant complex	Reworked Miocene pollen
Ceratopteris thalictroides (Pteridophyte), Cyperaceae	Microthyraceous (Epiphyllous) fruit bodies of various types. Spores of various morphological types – *Glomus* sp., *Frasnacritetrus* sp., *Meliolinites* sp., *Dendromyceliates splendus*, *Lirasporites* sp., *Dyadosporonites* sp., *Kutchiathyrites* sp., *Multicellaesporites* sp., *Phragmothyr-ites* sp., *Plochmopelti-nites cooksonii*	*Pandanus* sp. Palms (Arecaceae) *Hibiscus tiliaceus* (Malvaceae) *Sida cordifolia* (Malvaceae)	*Cheilanthes* sp. *Lycopodium* sp. *Lygodium flexuosum* sp. *Polypodium* sp. *Pteris/Pteridium* sp. *Schizaea* sp. Moss (bryophytes, representing cuticles/capsule opercula)	*Agrostistachys meeboldii* (Euphorbiaceae), *Cullenia exarillata* (Bombacaceae), *Fahrenheitia zeylanica* (Euphorbiaceae) *Lophopetalum wightianum* (Celastraceae), *Mallotus* sp. (Euphorbiaceae), Tricolpate pollen grain (dicot)	*Quilonipollenites* (pollen of extant palm of *Eugeissona* presently seen in the Malaysia and Indonesia). *Ctenolophonidites* of Warkali sediments, *Ctenolophon* at present seen in West Africa and Malaysia only

been found, except that of Malvaceae in the Pachcha profile (Figure 4 *b*).

Another important aspect of the palynological investigation is the recovery of a large number of diatom taxa in the palynological preparations (Figure 6 *e*–*j*). Till now, there has not been any comprehensive account of fossil diatoms for biostratigraphical analysis from the Indian subcontinent, except for the Neogene sediments of Neill Island, Andaman Sea[24]. Accordingly, there is scope to use these microfossils for biostratigraphic resolution of the Holocene sequence. Besides, the use of size changes of diatom valve as a biostratigraphic tool is significant in view of the fact that *Coscinodiscus nodulifer* (Figure 6 *e*) has large-sized individuals measuring more than 60 μm and was abundant during the glacial interval[25].

The reworking of Tertiary sediments in the Late Quaternary sequence as indicated by maturation level of palynofossils and certain plant taxa that became extinct

Table 4. Sedimentological, palynological, depositional environmental and palaeoclimate records in Ernakulam and Pachcha boreholes of SKSB

Depth (m)	Sediment characteristics	Palynological observations	Depositional environment/palaeoclimate
Ernakulam borehole (9°59′29″N–76°16′15″E)			
1.00	Greenish-grey, clayey sand with juvenile shells of molluscs.	Good recovery of organic remains; dispersed organic matter highly degraded forming amorphous materials; marine diatoms *Thalassiosira oestrupii* and *Triceratium favus* frequent; juvenile foram tests are common; dinoflagellates *Lejeunecysta* spp. (*Peridinium*), *Selenopemphix* spp. and *Polysphaeridium* sp. are frequent; spores of *Acrostichum aureum* and freshwater marshy pteridophytes – *Ceratopteris thalictroides* and *Lygodium* sp. are frequent; pollen of Liliaceae/Arecaceae and *Pandanus* sp. are well represented; pollen of *Cullenia exarillata* and Euphorbiaceae members of wet evergreen forests are rare.	Transition from marine to brackish water lagoonal environment with contribution from land and near-shore environments.
5.00	Light greenish-grey muddy sediment with juvenile shells/shell fragments of molluscan fauna.	More or less same as above, but the marine microplankton, especially foraminiferal tests are abundant; ostracods and dinoflagellates (especially *Multispinula quanta*) are common, littoral blue-green alga *Rivularia* sp. is also seen in the sample.	Brackish water lagoonal environment of deposition.
11.00	Greenish-grey, silty clay with juvenile shells of pelecypods and gastropods. Sediment sample between 10.0 and 10.1 m bgl is dated 5870 ± 160 yrs BP.	High recovery of organic remains; foraminiferal tests and dinoflagellates (*Lejeunecysta* and *Spiniferites*) are common, pollen of *Cullenia exarillata*, fungal fruit bodies and pollen of *Pandanus* sp. are common; littoral alga *Rivularia* sp. is abundant; high terrestrial input (C3 plants) and abundant fungal remains.	Brackish water lagoonal environment with heavy contribution from land and indication of heavy rainfall.
16.50	Light grey, silty clay with juvenile shells of molluscs. A sample between 15.7 and 15.8 m bgl is dated 6530 ± 130 yrs BP.	More or less similar to that of the above; marine influence and salinity are being reduced considerably; *Rivularia* sp. is common; marine elements are low and represented by dinoflagellates (*Spiniferites*, *Selenopemphix* and *Lejeunecysta*) and foram tests; pollen of *Cullenia exarillata* and Euphorbiaceae from highland/evergreen forests are abundant (C3 plants).	Transition from brackish to nearly freshwater environment with heavy terrestrial input suggesting heavy rainfall.
20.00	Greenish-grey, muddy sediment with broken and unbroken molluscan shells. A sample between 20.2 and 20.3 m bgl is dated 9250 ± 170 yrs BP.	Except for a few foraminiferal linings and dinoflagellates, no other marine microorganic remains are recorded; fungal spores as well as fern complex are common; cuticles of freshwater plants are abundant; *Botryococcus* (green alga, representing freshwater condition), inland/montane plant complex represented by *Cullenia exarillata* and Euphorbiaceae (C3 plants) are common at this level.	Freshwater to nearly freshwater lagoonal environment of deposition – dominantly continental deposition.
25.00	Light grey, sandy clay with nodular forms of iron oxide and organic matter.	High recovery of organic remains, mostly of continental origin; *Botryococcus* (green alga representing freshwater condition) well represented; cuticles of aquatic plants (freshwater) are common; no marine elements observed; spores and pollens of land plants are also rare at this level; spores of *Ceratopteris* fern of freshwater flood-plains have been observed.	Continental lagoonal (freshwater) environment of deposition.
Pachcha borehole (9°22′00″N–76°27′51″E)			
1.00	Light grey to grey, sandy mud with iron oxide nodules.	Organic recovery high; pteridophytic spores – *Lygodium* sp., *C. thalicteroides*, *Pteris wallichiana* are numerous; pollen of *Cocos nucifera* (coconut palm) and *Hibiscus tiliaceus* (Malvaceae) as well as phytoliths and plankton are seen; *Rivularia* sp. and microplankton are also present at this level.	Nearly fresh to slightly brackish water lagoonal environment of deposition. Absence of *C. exarillata* and other terrestrial wet evergreen forest pollen indicates decline in precipitation rate and deviation of wet climate.

(*Contd*)

Table 4. (*Contd*)

Depth (m)	Sediment characteristics	Palynological observations	Depositional environment/palaeoclimate
6.00	Light grey to black silty clay; a peat sample at a depth of 8.5 m bgl is ^{14}C dated 6990 ± 160 yrs BP.	Organic recovery high; pollen grains of *Cullenia exarillata* occur in abundance (C3 plants); pollen of *Pandanus* and a few foraminiferal linings are seen.	Nearly fresh to slightly brackish, lagoonal environment of deposition; heavy precipitation and prevalence of wet climate.
11.50	Greenish-grey to greyish-black clayey mud with abundant shells of gastropods and pelecypods.	Recovery of organic matter (palynodebris) is high and structured terrestrial materials occur in large quantity; pteridophytic spores abundant; marine inundation observed; foraminiferal tests and other microplankton are common.	Brackish water lagoonal environment of deposition; terrestrial abundance suggests dense forest floor and high humidity; abundance of *Cullenia* pollen suggests heavy rainfall and wet climate.
14.00	Light yellowish-brown to reddish-brown sandy mud.	Recovery of organic matter is very low; palynodebris is poor.	Continental environment (?) of deposition; change in biofacies as only spongy spicules are present; shift in climate probably indicating prevalence of dry spell.

from the west coast of India by the end of Neogene, is yet another significant observation of the palynological analysis. Notable examples are *Quilonipollenites* (pollen of an extant palm *Eugeissona*, presently seen in Malaysia and Indonesia) and *Ctenolophonidites* (pollen of extant *Ctenolophon*, at present growing in West Africa and Malaysia only). These two pollen taxa have been earlier identified from the Warkalli sediments (Miocene) of Kerala[13,14] and Konkan[26,27]. Their presence in trace amounts at 7.28 m level in Ramapuram borehole is a significant observation. The occurrence of reworked pollen in Late Quaternary sediments has significant climatic and phytogeographic implications because the above plant taxa do not occur anymore in the Indian subcontinent, particularly in Peninsular India. Probably, rainfall variations along with geomorphological changes have affected their habitats and their eventual displacement from southwest India. *Malvacearumpollis* (pollen of Malvaceae) recorded in the Miocene of Kerala is another reworked element invariably seen in some of the bore samples of the SKSB. The reworking of older sediments is also indicated by the occurrence of diatom species *Actinocyclus ehrenbergii* (Figure 6 *f*). The highest stratigraphic occurrence for this species is mid-Pliocene. Its presence in Kalarkodu, Pachcha and Ramapuram further confirms reworking of older sediments (Table 3).

Similarly, the palynotaxa represented by dinoflagellates, viz. *Spiniferites*, *Multispinula quanta*, *Lejeunecysta* spp., (Figure 6 *n–p*), *Selenopemphix nephroides* and *Thalassiophora* mostly common and restricted to the Tertiary, have been identified in some of the samples and as such indicate possibility of reworking of marine sediments in the Holocene sequence of the SKSB. *S. nephroides* does not go beyond the Miocene with reference to its global stratigraphic ranges[28].

Apart from this, the maturation level (on the basis of examination of colour in transmitted light under the microscope) of certain palynofossils reveals their high degree of thermal maturation (bright and dark colour) compared to those deposited in the recent past (Holocene), indicating reworking of older sediments. Such reworking of sediments has been observed in the Ernakulam borehole between 5 and 15 m depth, and at 5 m level in the Pachcha well.

Palynological analysis, including the study of palynodebris (Table 4) reveals heavy accumulation of organic matter probably contributed by the mangrove vegetation when the palaeo coastline was further away from the present one and the sea level was much lower along with high rainfall. This observation is significant at 12.0 m in the Pachcha well, 20.0 m in Ernakulam well, 35.0–39.8 m level in Kalarkodu and 10.85 m level in Ramapuram. In view of their significance, these organic deposits are to be dated to ascertain and fix the marine transgression event of Late Pleistocene–Early Holocene. Heavy accumulation of organic matter in marine sediments indicates extremely shallow-water conditions along the coastline. As mangroves are the most common contributors of organic matter in estuaries and situated generally in the inter-tidal region, they are directly related to the sea level at the time of deposition. The response of mangroves to environmental changes and the importance of mangrove pollen in distinguishing the facies change in the Late Quaternary of the west coast of India have been dealt with recently[29]. The presence of pollen of *C. exarillata* (Bombacaceae), a wet evergreen forest marker of the hinterlands in the high lands in these sediments indicates high rainfall as well. Accordingly, palynological analysis as well as ^{14}C dating of samples of close intervals have to be undertaken in order to address the Late Quaternary sea-level changes and sedimentation rate along the coast of Kerala. In fact, the heavy organic input probably due to high sedimentation rate at lower intervals may be attributed to relatively higher rates of weathering and erosion in the hinterland

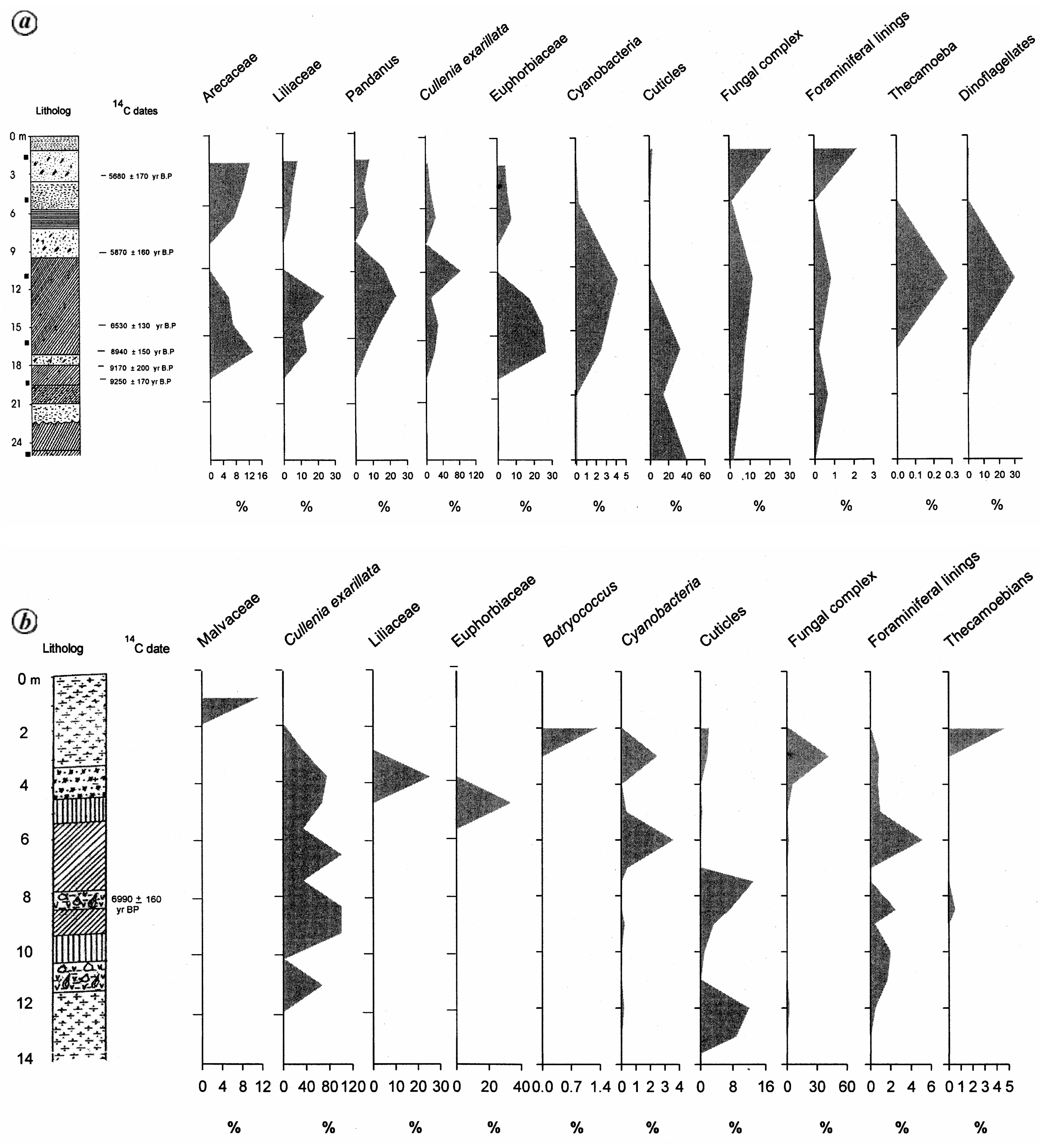

Figure 4. Profile diagram showing temporal changes of organic remains, including pollen and spores of Ernakulam borehole (***a***) and Pachcha borehole (***b***) (modified after Limaye *et al.*[33]).

as a result of high rainfall, since a more intense SW monsoon prevailed during Late Pleistocene–Early Holocene[11,12,23,30–33].

Detailed and high-resolution palynological analysis is needed for precise stratigraphic and palaeoenvironmental interpretation along with chronological data. Although we have palynological data of Early–Middle Holocene from a few boreholes that have been analysed till now, the Pleistocene and Late Holocene pollen data are required to appraise the environmental changes and vegetation response of southwest India. This can be achieved only if we analyse the samples at close intervals which have chrono-

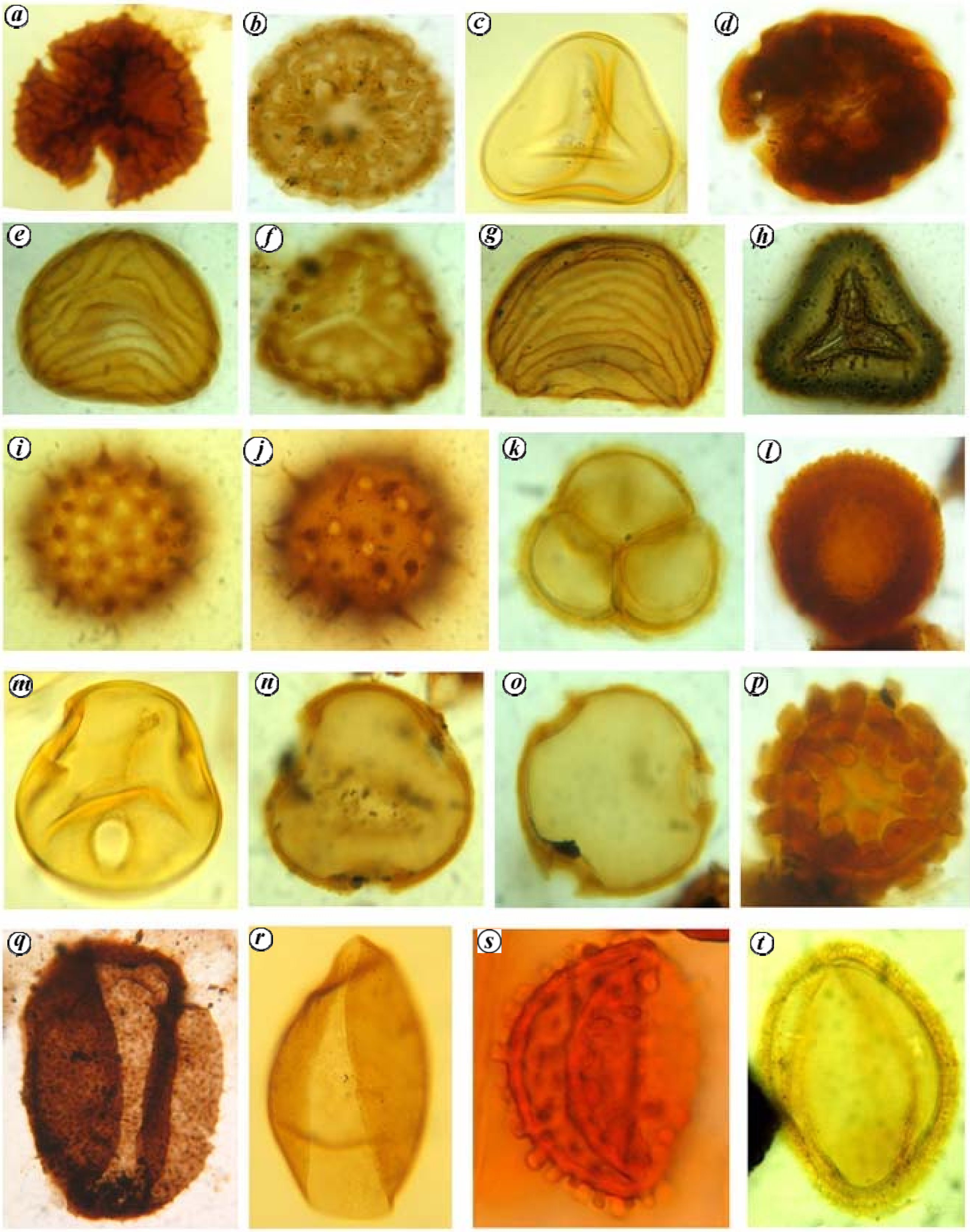

Figure 5. ***a***, *Lycopodium* sp.; ***b***, ***f***, *Lygodium* sp.; ***c***, *Gleichenia* sp.; ***d***, Reworked pollen (*Ctenolophonodites* sp.); ***e***, ***g***, *Ceratopteris thalictroides*; ***h***, *Pteris* sp.; ***i***, ***j***, *Hibiscus tiliaceus*; ***k***, *Lophopetalum wightianum*; ***l***, ***p***, ***s***, Euphorbiaceae pollen; ***m–o***, *Cullenia exarillata* (Bombacaceae); ***q***, Palm pollen; ***r***, Liliaceae pollen and ***t***, *Excoecaria agallocha*? (All photomicrographs are enlarged ca. ×500).

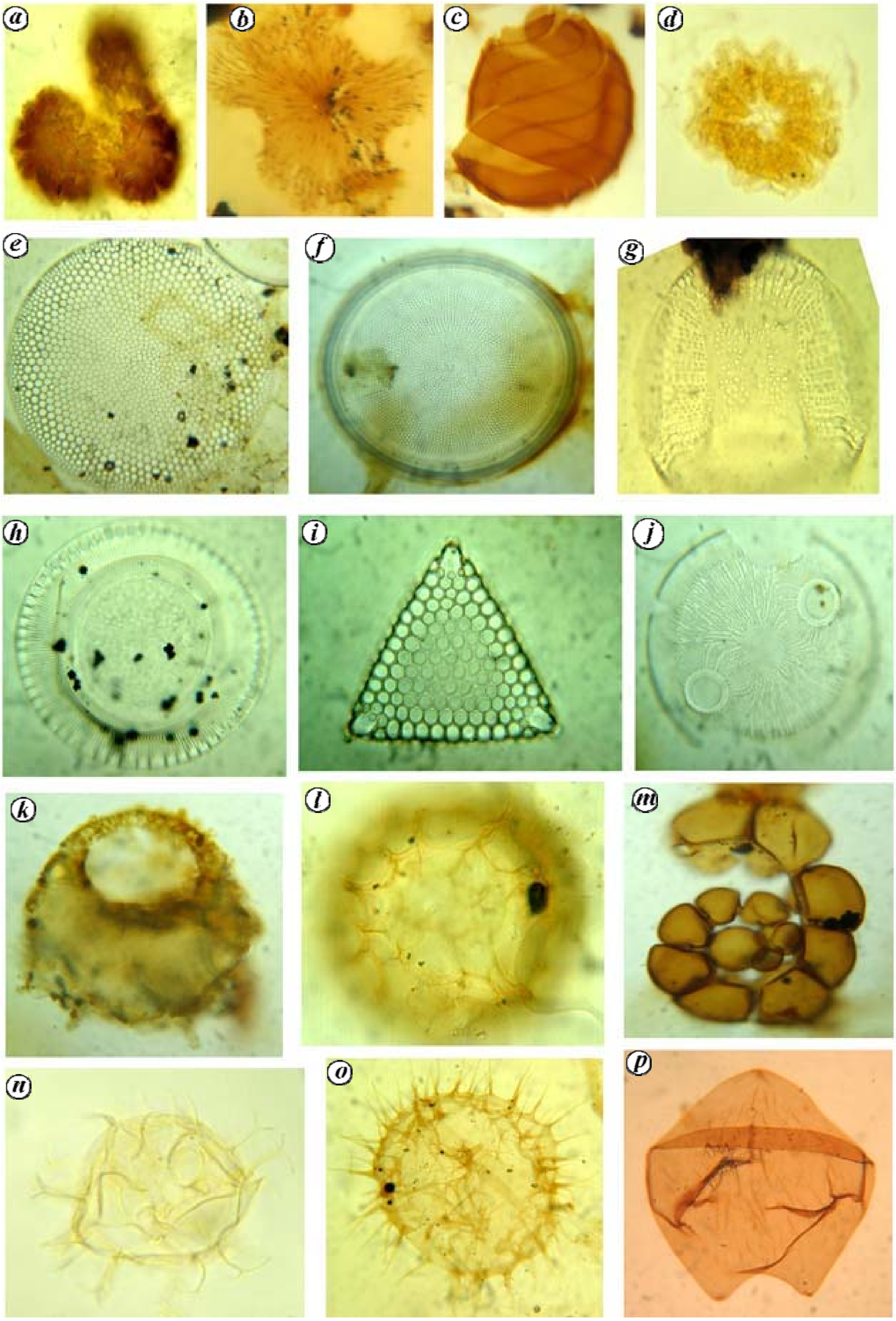

Figure 6. ***a***, *Botryococcus* sp.; ***b***, *Rivularia* sp. (cyanobacteria); ***c***, Oospore of *Chara*; ***d***, *Heliospermopsis* sp. (salt gland); ***e***, *Coscinodiscus nodulifer*; ***f***, *Actinocyclus ehrenbergii* (? Miocene diatom); ***g***, *Cymbella* sp.; ***h***, *Cyclotella striata*; ***i***, *Triceratium* sp.; ***j***, *Auliscus punctatus*; ***k***, Thecamoeba sp.; ***l***, Unidentified dinocyst; ***m***, Foraminiferal lining; ***n***, *Spiniferites* sp.; ***o***, *Multispinula quanta* and ***p***, *Lejeunecysta hyalina* (probably reworked from Miocene form). (All photomicrographs are enlarged ca. ×500.)

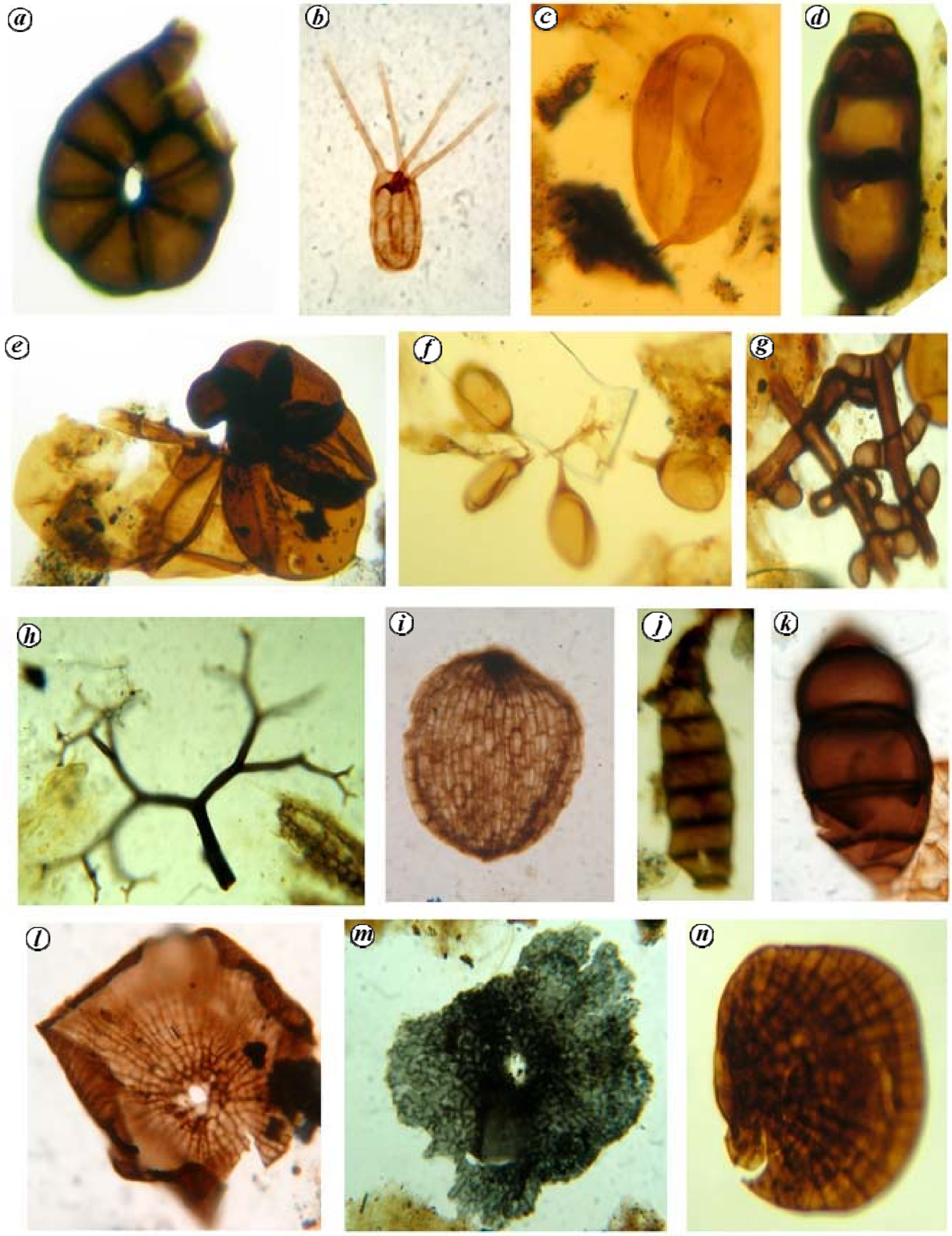

Figure 7. ***a***, ***e***, *Cirrenalia tropicalis*, mangrove-associated marine fungus; ***b***, *Frasnacritetrus* sp.; ***c***, ***f***, *Glomus* sp.; ***d***, *Dyadosporonites* sp.; ***g***, *Meliolinites* sp.; ***h***, *Dendromyceliates splendus*; ***i***, *Lirasporites* sp.; ***j***, ***k***, *Multicellaesporites* sp.; ***l***, *Phragmothyrites* sp, ca. ×500; ***m***, *Plochmopeltinites cooksonii*, ca. ×500 and ***n***, *Kutchiathyrites eccentricus*, ca. ×500. (Photomicrographs of fungal remains are enlarged ca. ×1000, unless otherwise specified.)

logical data. Although it is possible to identify the different ecological complexes on the basis of recovered microfossils, precise palaeoenvironmental changes such as influx of freshwater into the sea, shifting of shorelines, transgressive/regressive phases, oscillatory marine influences and other palaeoclimatic considerations could be addressed if we undertake a critical study of palynoflora in a comprehensive way.

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