Non-pollen palynomorphs as potential palaeoenvironmental indicators in the Late Quaternary sediments of the west coast of India

Ruta B. Limaye[1], K. P. N. Kumaran[1,*], K. M. Nair[2] and D. Padmalal[3]

[1]Palynology and Palaeoclimate Laboratory, Geology and Palaeontology Group, Agharkar Research Institute, G.G. Agarkar Road, Pune 411 004, India
[2]Vakkom Moulavi Foundation Trust, Thekkummoodu Junction, Thiruvananthapuram 695 037, India
[3]Centre for Earth Science Studies, Akkulam, Thiruvananthapuram 695 031, India

Non-pollen palynomorphs (NPP) are organic-walled microfossils that one frequently come across in palynological preparations during pollen analysis. Like pollen and spores they are more resistant to corrosion, and as such they too get preserved but not destroyed during maceration using HF and other strong acids. They provide an alternative source of palaeo-information where there is scarcity of pollen and spores in the sediments. Records of NPP in the Late Quaternary sediments form a valuable addition to the pollen-spore data of the lagoonal sediments of Kerala and the pollen pauper deposits of Gujarat coast, as not much palynological data are available from the west coast of India. The occurrence of *Botryococcus*, *Pediastrum* and colonies of *Rivularia* (cyanobacteria) in the Holocene sequence has considerable significance to ascertain the hydrological changes associated with the evolution of lagoons of the Kerala basin. *Glomus* cf. *fasciculatum* and thecamoebians are useful in the interpretation of soil conditions associated with aridity/stressed environment along the Gujarat coast. The abundance of microscopic charcoal and charred epidermal fragments of Poaceae (grasses and like forms) is related to fire-associated events, including that of human impact. Thus, the palaeoenvironmental indicator value of NPP is evident from the Late Quaternary deposits of the west coast of India. Study of these non-pollen microfossils has helped develop a new database on them. Further, a combined approach of pollen and NPP allows for better understanding of palaeoecological changes and also to assess the relative importance of climate change during the Holocene.

Keywords: Late Quaternary, non-pollen palynomorphs, palaeoenvironmental indicators, west coast of India.

NON-pollen palynomorphs (NPP) are often completely overlooked while studying palynological assemblages retrieved from the Quaternary sediments of India. This is due to lack of awareness and scarcity of literature to identify non-pollen objects that can be easily distinguished on pollen slides. Nevertheless, the paucity of spores and pollen grains in the sediments necessitates looking for alternative forms for interpretation of palaeoenvironmental conditions. This is particularly true for pollen pauper sediments where terrestrial input is scarce and the deposits formed during relatively long drier periods. In such cases they can serve as index fossils and environmental indicators. Considering the above, NPP constitute an important component of the palynological and microfossil data for palaeoecological information.

Due to sporopollenin-like composition (a resistant material of pollen and spores) of the outer layer, most of the NPP are well preserved in deposits and are not destroyed during chemical treatment of samples. They have their own story to reveal while ascertaining the ecological conditions under which they are being grown and deposited. The ecological importance attributed to these little-known fossils from India forms additional source of information to supplement palynological analysis of the Quaternary sediments while inferring the palaeoclimatic scenario of the concerned period. In the literature they are designated as 'extra fossils' or even categorized into 'palynodebris'[1]. However, a recent study of the NPP from a palaeoecogical point of view has gained much attention[2,3]. This is because sometimes palynomorphs derived from the vegetation are scarcely present in palynological preparations. Accordingly, many of these palynomorphs may be considered as potential environmental indicators to assign specific ecological conditions and palaeoclimate reconstruction of the Late Quaternary of the west coast of India. No detailed work as far as palaeoenvironmental interpretation based on palynofacies of the west coast of India has been reported, except some recent reports[4–7], and preliminary reports of palynological features and the non-pollen component records[8–14]. Our investigations on the west coast of India since 1998 have helped amass a good amount of NPP from different locations, which form the subject of matter in the present article.

Background, material and methods

All the samples were from the subsurface sediments of the coastal tract of three different sedimentary basins of

*For correspondence. (e-mail: kpnkumaran@gmail.com)

Kerala, Konkan and Gujarat (Figure 1) and most of them were retrieved by continuous and uncontaminated cores, except that of Adari (Konkan) and Lothal (Gujarat) from where trenches had to be made. Three types of materials were found to be fairly rich in organic matter and NPP. They were mudflats, most dominant feature of northern coast of Gujarat (Navlakhi) and Maharashtra (Aravi); brown-to-black clay from Lothal and carbonaceous clays from Adari, Pachha and Ernakulam (Kerala). The samples were processed by conventional method of separating organic-walled microfossils from that of sediments used in palynological preparations[15–17]. Besides, additional methods have been improvized from time to time for better recovery of NPP. Some testate amoebae, foraminiferal tests and a few siliceous forms along with charcoal fragments containing phytoliths withstood the HF used in palynological processing (Figures 2 *e*, *l* and 3 *a*, *e*, *f*, *l*, *n*, *o*). The figured specimens are kept in the pollinarium of the Geology and Palaeontology Group, Agharkar Research Institute, Pune, India.

Results

Besides spores, pollen and finely divided fragments of plant tissues, palynological preparations often contain a fair amount of other microfossils of varied natural affinities.

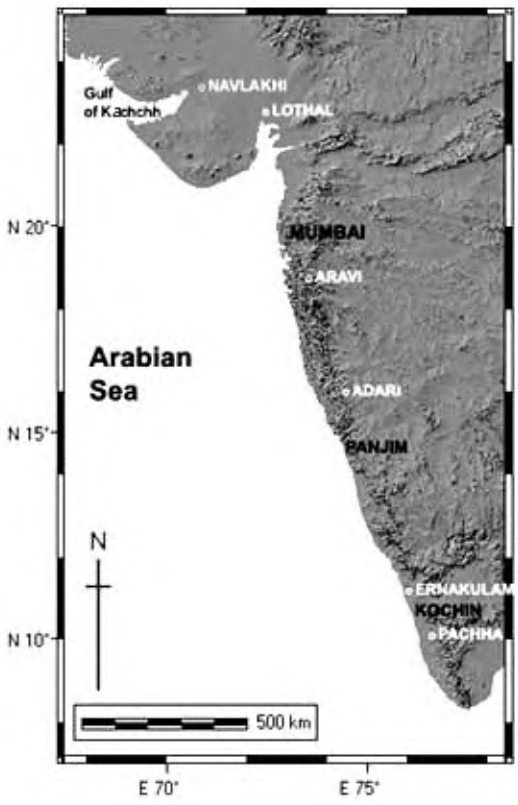

Figure 1. Location map showing selected sites (O) of the study area (modified after Kumaran *et al.*[6]).

Many of them are identified, but in a few cases identification is debatable and hence they are challenging objects for palynological research and palaeoenvironmental interpretation. These palynomorphs contain resistant organic molecule usually sporopollenin, chitin or pseudochitin, due to which they can withstand treatment with conc. HF. The various types of NPP recovered from the west coast of India and their probable affinities along with their characteristic features, distribution and relevant palaeoecological implications have been given in Table 1.

Algal palynomorphs form the most dominant NPP in the sediments of the west coast of India. The identifiable forms include Zygnemataceae, *Botryococcus*, *Pediastrum*, *Chara* sp. of freshwater green algae and *Rivularia–Gleotrichia* spp. of cyanobacteria. Next in abundance is that of fungal remains comprising spores, hyphae and fungal fruiting bodies. Further, pollen and spores of plants are few in number; vegetative remains in the form of cuticles, phytoliths along with cuticles and charcoal pieces, salt glands and epidermal growth (trichomes) are common in the coastal sediments. In addition, a few seed remains have been found along with vegetative remains. The invertebrates are well represented in the form of rotifers, scolecodonts (polychaete mouthparts), organic inner linings of foraminifers (foraminiferal linings) and smaller (juvenile) tests of certain protists. The other important group includes the thecamoebians of the Protozoans besides some sponge spicules (Figure 3 *f*) and their related forms. Considering the above, NPP constitute an important component of the palynological preparation, particularly in the Late Quaternary sediments and as such they complement the palynological and microfossil data for palaeoecological condition. A brief account of the different types of NPP is given below.

Micro algae

Freshwater algal palynomorphs are encountered in the lagoonal deposits of Kerala basin together with pollen and spores of terrestrial and aquatic vascular plants, cysts of dinoflagellates and acritarchs and fungal spores. These are mainly represented by *Botryococcus* sp., *Pediastrum* sp., *Chara* sp., *Rivularia* sp. and *Veryhachium* sp. (Figure 2 *b*). All these forms are microscopic and are well preserved as they possess sporopollenin-like substance.

Botryococcus sp.

It is a colonial green alga of order Chlorococcales with densely packed conical–cylindrical cells radiating and branching from the centre of the roughly spherical colony (Figure 2 *i*). Modern forms flourish in freshwater lakes, ponds and temporary pools, the dead cells sometimes accumulating to form an oily deposit. This oil-forming alga ranges in size from 5 to 60 μm, is known from Ordovician

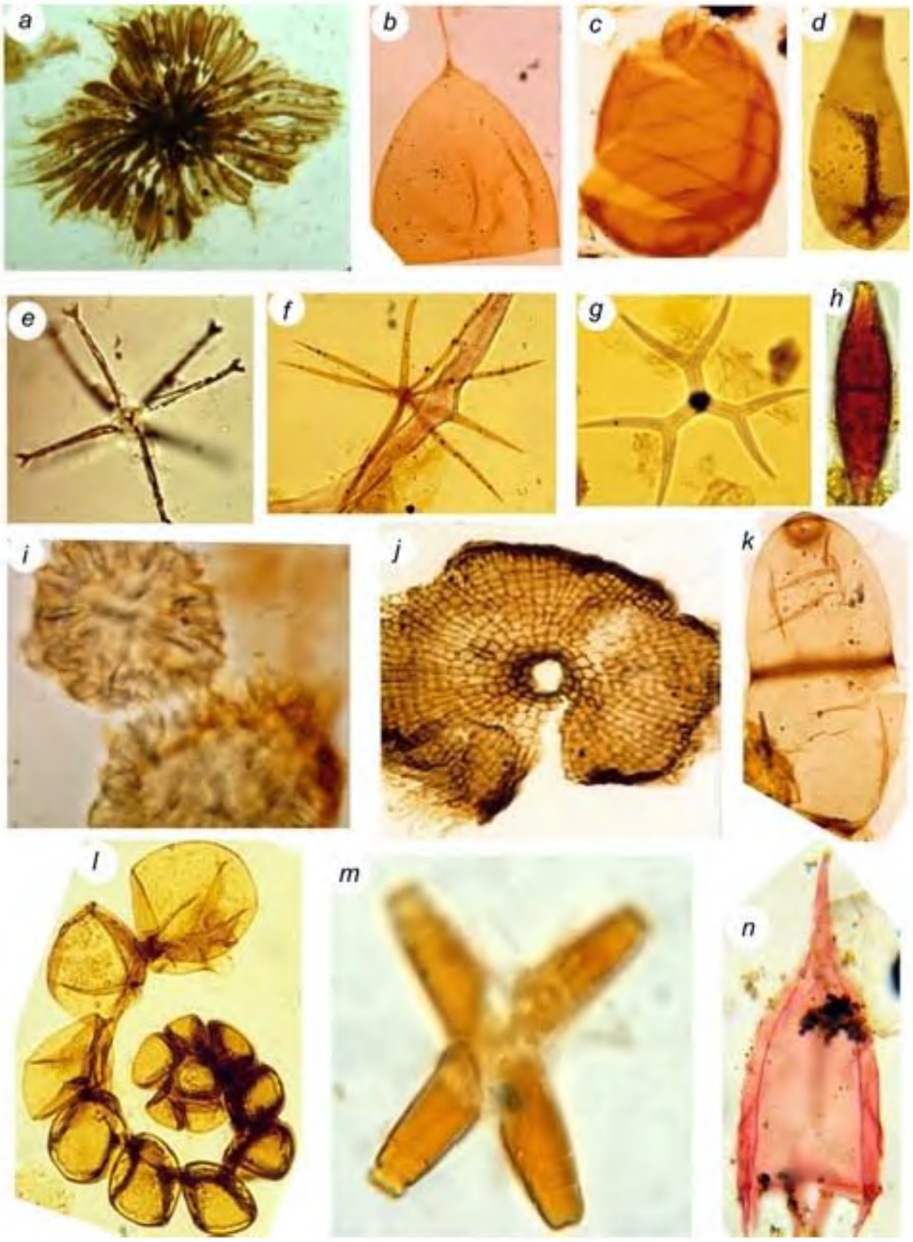

Figure 2. Photomicrographs of NPP from the west coast of India (magnified ca. × 500 unless otherwise specified). ***a***, *Rivularia* sp. (cyanobacteria) showing colony of sheaths. ***b***, *Veryhachium* sp. ***c***, Oospore (*Chara* sp.) ca. × 100. ***d***, Rotifer (*Callidina* sp.). ***e***, *Bacteriastrum* sp. ***f***, Trichome. ***g***, ***h***, ***m***, Sponge spicule (invertebrate). ***i***, *Botryococcus* sp. ***j***, *Trichothyrites* sp. (microthyriaceous fungal fruiting body). ***k***, *Diporisporites* sp. ca. × 1000. ***l***, Foraminiferal lining. ***n***, Zooplankton.

onwards and is associated with the formation of oils and bog-head coals[18]. Although Niklas[19] has shown that both extant and fossil *Botryococcus* possess an extraordinary diverse suite of organic compounds, the walls of the colonies that are preserved apparently consist partly of waxy hydrocarbons, besides sporopollenin. Though it is a freshwater form, it tolerates salinity to a certain extent, as it is known from various lacustrine deposits. Palaeoenvironmental significance of *Botryococcus* has been dealt within earlier works[19–22].

Pediastrum sp.

Pediastrum is another freshwater chlorococcalean, planktonic and green alga belonging to Chlorophyta, frequently found along with pollen and spores. The various species of this alga range from early Cretaceous to the Present. Although multicellular, it is more precise to refer to it as a green algal coenobium, as the number of cells is fixed at the origin of the organism. Being fairly delicate and cellulosic and at the same time resistant to biodegradation, it

Figure 3. Photomicrographs of more NPP types from the west coast of India (magnified ca. × 500 unless otherwise specified). ***a***, Calcium oxalate crystal. ***b***, *Heliospermopsis* sp. (salt gland). ***c***, *Pediastrum* sp. ***d***, *Tetraploa* sp. (fungal spore) ca. × 1000. ***e***, *Discoaster pentaradiatus* (calcareous plankton). ***f***, Thecamoeba. ***g***, Seed ca. × 250. ***h***, ***j***, Scolecodonts (invertebrates) ca. × 250. ***i***, *Chara* globule. ***k***, *Glomus* sp. ***l***, Microforaminifera ca. × 100. ***m***, Unidentified fungal spore ca. × 1000. ***n***, Charcoal fragments containing phytoliths. ***o***, Fossil cuticle (? fern-type).

is likely that the walls must be impregnated with some additional substance related to sporopollenin. Colonies of this alga are present in the carbonaceous clays of Dhamapur (Konkan) and Lothal at certain intervals of the lithosections (Figure 3 *c*). These colonies are circular, star-shaped and made up of 8, 16 or 32 individuals with small lens-shaped perforations between cells. The inner cell is quadrate to angular and not in contact with the centre of the

Table 1. NPP from the west coast of India

NPP	Characteristic feature	Distribution	Palaeoecological implications
Micro algae			
Botryococcus	Colonial green and oil-forming alga, 5–60 µm	Freshwater to brackish water, cosmopolitan, Pachha (Kerala)	Lacustrine environment. Indicator of hydrological changes (freshwater input)
Pediastrum	Colonial green alga; 8, 16, 32 cells	Freshwater, planktonic, Lothal (Gujarat) and Konkan	Fresh to brackish water condition. Indicator of hydrological changes (freshwater input)
Bacteriastrum	5–6 arms	Marine	Marine planktonic environment
Oospores and gyrogonites of *Chara*	Organic oogonia with spiral bands and coronular cells, calcified gyrogonites	Freshwater to brackish water, west coast of India (Kerala, Gujarat)	Suggestive of brackish-water sedimentary environment. Proxy for seasonal water bodies (meteoric water)
Cyanobacteria			
Rivularia	Colonial blue-green algae (heterocyst and trichomes)	Freshwater to brackish water, cosmopolitan, Pachha (Kerala), Aravi (Konkan)	Phosphate eutrophication of water bodies. Proxy for wetland evolution
Fungi			
Spores (*Glomus*)	Chlamydospores variable in size, 18–138 µm in diameter, exclusive of hyphal attachment	Lothal (Gujarat), Karalimukku (Kerala)	Erosion aspects around the area
Fruiting bodies (Microthyriaceae)	Multicellular microthyriaceous	Higher altitudes, humid areas, Konkan and Kerala	Epiphyllous forms, particularly on fern foliages. Indicates high humidity and heavy rainfall
Hyphae (*Dendromyceliates*)	Unicellular to multicellular dichotomously branched, made up of chitin	Higher altitudes, humid areas, Konkan and Kerala	Indicative of high organic input and heavy rainfall
Vegetative remains			
Cuticles	Outer protective covering, displays features such as stomata and glands	Navlakhi (Gujarat), Pachha (Kerala)	Higher terrestrial (allochthonous) abundance of inland evergreen types suggests wet conditions. Proxy for palaeotemperature
Phytoliths and phytolitharians	Silica bodies, mineralized microfossils and epidermal casts	Pachha (Kerala), Navlakhi (Gujarat)	Determines vegetative types in a particular locality. Interpretation of palaeoflora and palaeoclimate. Proxy for agricultural practices
Microscopic charcoal	Jet-black coloured particles in palynological preparations	Navlakhi (Gujarat), Pachha (Kerala)	Suggestive of evidence of a fire in the past. Reconstruction of local fire episodes
Trichomes	Epidermal appendages of diverse form, structure and function	West coast – Aravi (Konkan)	Protection from insects and prevents rate of transpiration. Indicative of arid conditions/mangrove ecosystem
Heliospermopsis sp. (salt gland)	Glandular and organic in nature, stellate-type	Konkan and Kerala	Affinity with mangrove swamp/coastal vegetation
Seed coat	Developed from ovule at maturity	Pachha (Kerala)	Aquatic/microscopic seed remains suggestive of marsh flood plains/swamps
Invertebrates			
Scolecodonts	Chitinous mouthparts of marine annelid worms in form of jaws and maxillae, 100–4000 µm	Beach or near shelf, Pachha (Kerala)	Shallow marine deposits
Microforaminiferal linings	Very small forams, chitinous inner tests of foraminifera	Lothal (Gujarat)	Marine incursion at the time of sedimentation. Proxy for sea-level oscillations
Sponge spicules	Siliceous, lumpy spicule	Navlakhi (Gujarat)	Marine affinity
Thecamoebians	A simple, sac-like or cap-like test, agglutinated or autogenous test	Freshwater to slightly brackish water environments	Abundance indicates lacustrine sediments. Indicative of contamination, acidity and pollution. Proxy for stressed environmental conditions
Rotifers	Thick-walled, tubular, flask-shaped bodies, size ranges from 50 to 2000 µm, pseudochitinous	Pachha (Kerala)	Local stratigraphic correlation and seasonal rainfall indicators
Tasmanite	Hollow, spherical-to-lenticular fossils with a thick organic wall. Size range up to 50 µm	Lothal (Gujarat)	Lacustrine environment

sidewalls. Modern analogues of this alga are green and float in ponds, marshes, lakes, rivers and pools. Its growth depends upon the intensity of light that it receives, the warm temperature and amount of nutrients in water. Fossil *Pediastrum* is an indicator of fresh- to brackish water conditions of deposition[23]. Batten[24] observed that occurrence of *Pediastrum* sp. in pollen preparations indicates a wide range of environmental responses. Factors attributed to such responses include changes in erosion in the catchment area, turbidity, water chemistry, nutrient status and pH. Study of fossil forms along with modern analogues will be useful to address the importance of this colonial green alga as a potential environmental indicator for Late Quaternary sediments, especially while ascertaining hydrological changes associated with the evolution of wetland systems, including lagoons.

Chara sp.

The oospores (oogonia) of *Chara,* usually preserved as fossils in detached form are characterized by coronular cells that vary in number (Figure 2 *c*). They are found in the Pachha, Dhamapur and Gujarat samples. The species of *Chara* are seasonal plants and depend on freshwater sources, mainly meteoric source. Charophytes develop new forms in each period, which soon become extinct, and hence they are used as stratigraphic markers[25]. As the charophytes are seasonal species solely depending upon freshwater, their occurrence in the coastal deposits can be used to address aspects of palaeoclimate where there is scarcity of pollen and spores of higher plants. The gyrogonites (calcified oogonia) of *Chara* are common in the Late Holocene sequence of the Gujarat coast[26]. Their relative abundance at different stratigraphic levels is of significance to ascertain the palaeoclimate, as the production and preservation of such bodies is proportionate to the rainfall. Despite the occurrence of such well-preserved remains of *Chara* in the lake and coastal deposits, its potential application as proxy in palaeoclimate study is yet to be exploited.

Cyanobacteria

Formerly known as blue-green algae, these microscopic forms represent a link between bacteria and green plants. Their occurrence allows us to interpret the changing local environments in lakes and ponds in the past. Since cyanobacteria are capable of nitrogen fixation, their abundance indicates environmental conditions suitable for the growth of aquatic macrophytes due to nutrient enrichment from agricultural run-off and other induced factors. We have observed them at certain intervals of the subsurface sediments of the Kerala basin and their presence indicates poor nitrogen conditions in the environment of deposition. Cyanobacteria (*Rivularia* sp.) are found to be dominant in Pachha, Ernakulam and West Kallada (South Kerala sedimentary basin), indicating eutrophication in this region during certain intervals (Figure 2 *a*).

Modern *Rivularia* forms are microscopic colonies of spherical, hemispherical or irregular gelatinous masses that grow on plants, stones or soil. They are free-floating and photosynthetic. The fossil forms of this cyanobacterium belong to family Rivulariaceae, order Nostocales. Each colony contains numerous filaments, the trichomes of which are often terminated by colourless hairs. Sheaths protect the basal part of the trichomes. Majority of the cells produced are vegetative; two other kinds may form a structure called heterocysts and akinetes, which differ in size and appearance. Fossil records of Rivulariaceae as such are scanty in India. There are only three known records of this family. These are *Primorivularia* from the Kushalgarh Formation of the Delhi super group, Rajasthan; three species of *Rivularia* from the Cretaceous of Tiruchirapalli District, Tamil Nadu and records from Tertiary of Kachchh by Mandal[27]. It is inferred that *Rivularia* spp. are most abundant during the periods when there is incursion of salt water[28]. The distribution can be interpreted as 'blooms', indicative of certain recurring salinity levels. Alternatively, it could represent seasonal phases of high productivity, pH neutral or slightly alkaline.

Fungal remains

Studies on fossil and sub-fossil fungi in India are few and far between, as their utility in geological aspects has been seldom addressed despite their occurrence in lignites, peat and carbonaceous clays. Their presence along with spores and pollen of terrestrial vegetation in sediments has gained much attention in view of their utility in facies determination, interpreting palaeoenvironmental conditions and stratigraphic relationships of sediments[29–32]. Considering their abundance in Cenozoic and Quaternary deposits of the west coast of India, they have been found to be useful and complement palynological data of terrestrial plants[33]. Some fungal spores are so distinct that they can be identified with unequivocal reliability and accordingly, a restricted range in geological time as well as distinct bases to their total ranges. Not much attention has been paid to utilize this group of NPP for palaeoecological and palaeoenvironmental interpretation despite the fact that they provide evidence of relative humidity, atmospheric pressure and heavy precipitation rates[34]. The relative abundance, host specificity and habitat preferences of these have significant implications in palaeoenvironmental study. A variety of fungal materials representing spores, fruiting bodies and fungal hyphae are present in the palynological preparations in most of the samples studied. Spores vary from unicellular to multicellular (Figure 3 *d*, *m*). The globose chlamydospores of *Glomus* sp. (Figure 3 *k*) are extremely variable in size (18–138 μm) exclusive of the hyphal attachment. Erosion in the area around the lake accounted for the abundance of *Glomus* in the Late Glacial sediments. The reduced abundance in Holocene sediments was attributed to a decrease in the rate of soil erosion and related sedimentation in the lake after the establishment of forest[35]. Hyphae associated with *Glomus* are most probably locally deposited as they are found in abundance at certain intervals belonging to the supratidal soil environment of Lothal and Navlakhi, Gujarat basin[14,36]. *Diporisporites* sp. (Figure 2 *k*) is another form found in sediments of the Kerala basin (Ernakulam).

Fungal fruiting bodies

Fungal fructifications are multicellular, microthyriaceous, vary in size, and are found in organic-rich sediments (Figure 2 *j*). Since they are epiphyllous fungi, their occurrence must be related to foliages derived from the land plants, including coastal swamps. Though the modern analogues are known to infect both coniferous and angiosperm leaves, their occurrence in the Quaternary deposits of the west coast is attributed to accumulation of terrestrial vegetation belonging mainly to the dicotyledonous angiosperms. However, forms of fruit-bodies have also been reported from peat vegetation mainly composed of *Sphagnum*[31] and the *Pteris* foliages of the Kerala basin. The fungal fruiting bodies are composed of chitin and pseudochitin and show remarkable resemblance to ascocarps, thyriothecia or ascostromata of the microthyriaceous fungi, order Hemisphaeriales of Ascomycetes. A few families, such as Meliolaceae, Microthyriaceae and Micropeltaceae are recognizable by their non-sporic, easily fossilized organs[37]. The distinctive morphology of the sexual reproductive bodies of these fungi is easily identifiable on pollen slides. Several types of mostly strongly flattened fruit-bodies referable to *Trichothyrites*, *Callimothallus*, *Phragmothyrites*, *Euthyrites*, *Plochmopeltinites* and *Trichopeltinites* are common in the studied samples. The mycelial fragments bearing characteristic capitate hypophodia are referred to as *Meliola* sp. while the fossil forms are assigned to *Meliolinites*[29]. Most of the fruit bodies still contained ascospores, and sometimes the ascospores had germinated before fossilization that takes place from one or both of the terminal cells of the ascospores. Meliolaceae are obligate and rather oligophagous parasites on green plants. They occur most frequently in the dry peat developed at elevated levels and away from the coast. As most of them are found detached from the associated epidermis/cuticle, it is difficult to assign the host specificity of these fungi. Although dispersed fungal fruiting bodies are rarely found in association with mycelia and spores, they can be compared to modern analogues with greater accuracy than dispersed spores due to their complex morphology. However, bulk maceration may prove useful to identify the associated host plants and ecological implications displayed by the taxa. Fossil fructifications (ascocarps) of microthyriaceous fungi are generally considered to be reliable indicators of palaeoenvironment and their occurrences are correlated with moist, humid climates and tropical to subtropical temperatures[29]. More than the temperature, it is heavy rainfall that is considered essential for the abundance and rapid spread of the microthyriaceous fungi[38].

Fungal hyphae

Fungal mycelia made up of chitin are abundant in many samples of some of the intervals in the subsurface sediments. They are abundant along with spores in samples from Kerala. The most dominant form is *Dendromyceliates* and is conspicuous by the presence of dichotomously branched tip of the hyphae. Although the affinity is not known, the basal part of the hyphae shows some disc-like parts, which perhaps points out that the hyphae were attached to some other organ, probably on an ascocarp[39]. *Gaeumannomyces* sp. hyphopodia parasitic on *Carex paniculata* and *C. pseudocyperus* of Cyperaceae, are found in sediments of the Konkan coast. These hyphopodia are borne on side branches of the dark-brown mycelium and are irregularly lobed with blunt lobes. These lobed hyphopodia appeared to be characteristic for the local occurrence of *Carex* sp. As they play a role in lake margins and shallow phases of wetland bodies, records of hyphopodia could be useful for palaeolimnological study and history of lagoonal deposits. Higher frequency of this fungus is probably suggestive of a freshwater marsh/floodplain environment. Dominance of fungal complex as such is indicative of high organic input and heavy rainfall[4].

Vegetative remains

Organic materials, mainly of plant remains, are found in abundance in palynological preparations. Their recovery is better in Kerala and Konkan and poor from Gujarat. Cuticles along with phytoliths, salt glands, charcoal, trichomes and seeds are some of the few forms that are briefly dealt below.

Cuticles and phytoliths

These were found in the form of fragments in palynological analysis during the present investigation. The cuticle is the outer protective layer of the skin of leaves and is made up of cutin, a resistant material, which helps in the fossilization process. It cleary displays the cell pattern of the underlying epidermis, including features such as stomata and glands. The cell pattern is unique and each plant species has its own characteristic cuticle. They are used as an aid in interpretation of climatic changes at major boundary events[40]. The cuticles offer additional source of evidence, potentially of value for recognizing taxa of plant and for identifying local rather than long-distance input. They also provide information on palaeoecology based on quantitative analysis of the stomata in relation to time and space.

Phytoliths in the form of mineralized microfossils are usually found along with the cuticles and microscopic charcoal (Figure 3 *n*). These are silica bodies and other silicified plant parts, such as silicified hairs and cell walls occurring in soils, dust, etc.[41]. They are formed inside plant cells (especially epidermal cells) and exhibit characteristic shapes. The most common are plant opal phytoliths formed from silica, well known from epidermal cell of grasses. The study of phytoliths in soils is valuable for determining the vegetation types in a particular locality where pollen analysis is weak, as in the recognition of herbaceous and arboreal taxa of mature tropical rainforests[42]. Fossil phytoliths provide additional information in reconstructing vegetation, enabling the discrimination of vegetation types and agricultural activities generally unavailable in conventional pollen and carbon isotope analysis. The diverse phytolith morphotypes discriminate forest and shrub vegetation dominated by C_3 plants from C_3/C_4 grasses that are adapted to various soil environment and climatic conditions. Phytoliths and pollen grains are complementary tools of palaeoenvironmental reconstruction and should be studied in tandem whenever possible. Fossil opal-phytoliths can play an important role in the interpretation of palaeoflora and palaeoclimate and their utility is seldom exploited in the Indian context.

Phytolitharians

Opaline silica bodies that accumulate in the epidermal cells of grasses and allied plants are released on oxidation of the vegetal tissues as microscopic particles. This is a less known group of silicified casts of epidermal cells and is seldom reported from Indian sediments[43]. These remains come across in the palynological preparations of the coastal sediments. Though Twiss *et al.*[44] recognized four classes, elongate with irregular spines and spiny sclerites with club-like ends are common in the Late Quaternary sediments of the Kerala basin. Detailed study of phytolitharians from different geographical regions and age may add more morphological groups, which in turn will help interpret palaeoenvironment, provenance and biostratigraphy.

Salt glands

These are in the form of tiny pores seen on the upper surface of the mangrove leaves. *Heliospermopsis* sp. commonly occurs in salt glands (Figure 3 *b*). The main function of these salt glands is salt excretion in order to regulate the amount of salt in the plant sap to survive in sea water. Presence of salt gland in the coastal sediments signifies that the palynoflora has an affinity to mangrove swamp/coastal vegetation.

Charcoal

Charred epidermal fragments of grasses (Poaceae), the jet-black remains in palynological preparations are referred to as microscopic charcoal (Figure 3 *n*). Charcoal analysis of sediments along with pollen data from the same cores are used to examine the linkages among climate, vegetation, fire and sometimes anthropogenic activities in the past[45]. Their occurrence in the sediments may be as a result of natural fires (induced by lightning) or man-made. Naturally caused fires indicate drought conditions, whereas grass fires indicate that conditions preceding the fire were wet enough to accumulate fuel or combustible material. Grasslands tend to occur in semi-arid climate, so that prolonged drought means no grass can grow and thus there is little in the landscape that can burn. Sedimentary layers with charcoal abundance suggest evidence of a fire event in the past[46]. Further, microscopic charcoal particles (<100 μm in size) are carried high up during a fire event and can travel long distances before settling. A record of such particles provides a reconstruction of regional or extra-local fires.

Trichomes

Trichomes are epidermal outgrowths occurring on the foliages of plants that grow under stressful ecological environment. These special structures are much stronger than the other cells due to extra thickening of the outer walls of the cells by cutin or related material; and as such their chances of preservation are considerably greater in sediments along with pollen and spores. The epidermal appendages are of diverse form and structure, and are specially adapted to different functions. There are unicellular to multicellular types commonly found on pollen slides, but the stellate types (Figure 2 *f*) are frequently found in coastal deposits of West India. It is known that the trichomes provide extra protection to plants that grow in adverse or arid conditions in order to prevent desiccation and also protect them from insects attack. In physiological drought conditions (as in mangroves), trichomes (hairs on *Avicennia* and *Derris heterophylla*) prevent water loss and help maintain leaf temperature. Accumulation of such forms in the sediments and their relative abundance in the palynological preparations have definite ecological implications and accordingly, the trichomes can also be addressed while interpreting the palaeoclimate taking into account all the organic input data.

Seed

Being the hard and toughest part, seed remains, particularly microscopic types (150–250 μm in size) are associated with pollen slides of coastal sediments. These morphological types are assigned to an artificial genus *Spermatites* in palynological literature, despite the fact that a few angiosperms, both monocots (Poaceae, Cyperaceae, Hydrocharitaceae, Aponogentonaceae, Potamogetonaceae, Blyxaceae) and dicots (Polygonaceae, Lythraceae, Acanthaceae), produce such forms distinguishing them from other palynomorphs which can be easily recognized on pollen slides. Since many taxa of the above families inhabit the wetlands and associated marshes, accumulation and preservation of their seeds in the coastal deposits have considerable ecological significance. Although a seed is developed from an ovule at maturity, the seed coat (testa) develops from that of the hardest part, i.e. the integument. During the maturation of seed the testa undergoes varied degrees of structural alterations, but the seed coat withstands the decaying process during fossilization and remains preserved. The relative abundance and accumulation of such seed remains at different stratigraphic levels can complement pollen data for interpreting the palaeoenvironment and vegetation history. A few such seeds have been recovered from Pachha (Figure 3 *g*) and the details are being addressed elsewhere.

Invertebrates

Invertebrate remains belonging to sponge spicules (Figure 2 *g*, *h*, *m*), mouthparts of some insects and worms, aquatic insects, mites, zooplankton (Figure 2 *n*) and even some cocoons that escape the acids used for maceration are often seen on pollen slides. However, these forms have seldom received attention of the palynologists and are hardly utilized while ascertaining the palaeoenvironment and palaeoclimate of the Quaternary sediments. Some of the significant remains that have been retrieved from the west coast and their ecological implications are briefly dealt below.

Scolecodonts

The chitinous mouthparts of marine annelid worms in the form of jaws or maxillae constitute the scolecodonts. Fragments of these are frequently encountered on pollen slides from conventional macerations. They are composed of acid-resistant chitinous substances. Size ranges from 100 to 4000 μm. These forms are mostly found in the Navlakhi sediments (Figure 3 *h*, *j*). Their occurrence in fairly good amount in the sediments is a useful indicator of the site of deposition being near shelf or beach environment.

Foraminiferal linings

Foraminiferal linings are the organic inner linings of juvenile foraminifers and they actually represent the chitinous inner tests (Figure 2 *l*). Although the lime skeleton is the sole character for identification of Foraminiferae, only the organic cast is preserved in the sediments, and as such it is difficult to ascertain their natural affinity such as genus or species for ecological and stratigraphical consideration. The size of these fossils ranges from 10 to 100 μm, and may be even more. They are mostly elongated, unilocular, uniseriate, biseriate and triseriate and coiling-type. Biserials and close-coiled forms dominate followed by *Globigerina*-type and loose-coiled forms. The chitinous inner linings of benthic foraminifera are common in pollen preparations of marine or estuarine sediments. Spiral forms and coiling are most common, but zigzag, linear and other forms also occur[47]. Such forms generally characterize hypo-saline lagoons and estuaries, and may also be found in intertidal and shallow water in coastal areas. It is unusual for foraminifera to escape destruction during palynological processing, including acetolysis. Nevertheless, similar instances have been recorded in Quaternary sediments[15,48]. The frequent occurrence in palynological preparations suggests exclusively marine condition. Further, foraminiferal chitinous inner tests show a distribution entirely different from the conventional palynomorphs (pollen and spores), presumably because the foram fossils are thanatocoenosis, related primarily to factors encouraging the development of foraminiferal populations.

Thecamoebians

Freshwater protozoans that form agglutinated or autogenous tests constitute the thecamoebians (Figure 3 *f*). They are also called Arcellaceans because their tests resist dissolution in low pH environments, unlike those of other freshwater organisms like molluscs and ostracodes[49,50]. Almost all fossilized aquatic thecamoebians possess xenogenous tests. The common factor of all thecamoebians is the presence of a simple sac-like or cap-like test normally, but not exclusively, with a simple aperture for the extrusion of pseudopods. They are benthic organisms that are well preserved even in low pH, freshwater sedimentary environments. Their abundance indicates lacustrine sediments. Fossilization occurs almost exclusively in forms living in lakes, bogs and rivers. The mechanism of encystment enables these organisms to populate dry areas and remain dormant until water brings them back to active life. They can be readily transported over a long distance by a variety of agents. These factors enable them to randomly reach any type of environment. Thecamoebians are used as environmental proxies as they are indicators of a variety of palaeolimnological conditions, including pH, eutrophication, oxygen level and heavy metal contamination[51,52]. However, they are found in freshwater to slightly brackish environments, including freshwater lakes, estuarine environment, salt and freshwater marshes, soil peat, moss under tree bark, ponds and standing water[53–57].

Rotifers

Rotifers are minute, usually microscopic but many-celled, flask-shaped bodies, single or in chains with thick tubular wall forms and such types occur in pools and peat deposits (Figure 2 *d*). They are mainly freshwater aquatic invertebrates having the anterior end modified into a retractile disk bearing circles of strong cilia that often give the appearance of rapidly revolving wheels. Their size ranges from 50 to 2000 μm and they are made up of pseudochitin. Some of them have been assigned to chitinizoans produced by graptolites[58], but natural affinity is towards rotifers such as *Callidina*. The chitinoid wall of these forms suggests that animal affinities, whether metazoan or protistan, are still uncertain. Such forms are seen only in Pachha. Dormant eggs of rotifers are also of regular occurrence in coastal deposits mostly derived from seasonal water-bodies. As the rotifer eggs remain dormant for a long period and comes to life immediately after the onset monsoon rainfall, their occurrence at different stratigraphical levels may provide additional palaeoenvironmental information. In the absence of other fossils, rotifers can be useful for local stratigraphical correlation.

Discussion

The utility of NPP for palaeoenvironmental change is seldom addressed in palaeoclimate study in India, despite the fact that they occur in palynological preparations of most sediments. Considering their value as palaeoenvironmental indicators[3], these microscopic entities offer important proxy data for palaeoecological and environmental changes and equally complement palynological data for higher resolution ecological changes and climate of the past. We have observed that their implications are significant in pollen pauper sediments deposited in arid and low-rainfall periods of the Holocene. Further, their occurrence along with palynomorphs of aquatic and terrestrial vascular plants in the lagoonal deposits of Kerala basin, is of immense significance in the reconstruction of lagoons and Holocene evolution of the region associated with climatic changes and sea-level oscillations. Accordingly, an attempt was made to identify the various kinds of NPP recorded from the Late Quaternary sediments of the west coast of India. There are still a large number of forms yet to be identified.

In order to develop a new database of NPP from the west coast of India, three different sedimentary basins were selected – Gujarat, Konkan and Kerala. This was done mainly because these three basins differ in rainfall pattern and organic recovery. Further, we wanted to make a comparison of NPP with that of pollen and spores for palaeoenvironmental reconstruction. In Gujarat, rainfall is scarce, approximately 33–152 cm and the rate of sedimentation is relatively low. Here preservation of spores and pollen is poor and being pollen pauper sediments, NPP form a significant tool for palaeoenvironmental reconstruction. Whereas in Konkan, the rainfall is 230–250 cm and rate of sedimentation is comparatively higher than the Gujarat basin and also the preservation of spores and pollen is much better. Kerala basin receives rainfall twice from June to September (southwest monsoon) and October to December (northeast monsoon). Rainfall is heavy (about 400–500 cm) and the rate of sedimentation is higher than that of Gujarat and Konkan. Preservation of spores and pollen is much better in these sediments and also the NPP are well preserved. Accordingly, utility of NPP retrieved from different locations along the west coast of India for palaeoecological changes is being discussed.

A quantitative study in the form of pollen diagrams of Navlakhi (Figure 4), Aravi (Figure 5) and Pachha (Figure 6) has been attempted in order to compare with those of the NPP and to find out their implications in palaeoecology. In the Navlakhi profile, the NPP are well represented. Microscopic charcoal and microforaminiferal tests are the dominant groups. The low frequency of charcoal remains at ca. 140 cm level during the Early Holocene may be attributed to low incidence of forest fire-related events in the neighbourhood and at the same time an increase in marine forms (ostracodes, forams) indicates higher sea level. Besides, representation of terrestrial vegetation (pollen, spores, cuticles) is much less and this may be due to paucity of freshwater discharge/weaker monsoon in the Gulf of Kachchh. The prevalence of dry period/poor precipitation and lower humidity can also be envisaged due to negligible representation of fungal remains. Nevertheless, the higher frequency of pollen, spores, cuticles and *Chara* at certain levels, particularly at lower levels of the profile, suggests higher influx of freshwater into the region. Rajshekhar *et al.*[59] also observed similar climatic shifts, wet and dry periods based on foraminiferal composition and magnetic parameters. Thus, the utility of NPP in palaeoenvironmental reconstruction and palaeoclimatic deductions has been found to be significant and to complement the micropalaeontological and mineral magnetic data.

In the Aravi profile along the Konkan coast, recovery of NPP is much less compared to that of pollen and spores. However, cyanobacteria, fungal complex and foraminiferal remains are some of the major groups of NPP. There is not much change in the vegetation scenario as such since the pollen and spore frequency remains more or less same throughout the profile. The only ecological change that we can envisage in this region is abundance of cyanobacteria at higher levels in the profile. This may be due to local 'bloom' in neutral or slightly alkaline conditions or perhaps seasonal changes associated with rainfall conditions/freshwater influx. The fungal turnover towards the top of the profile is suggestive of prevalence of wet conditions and higher humidity in Konkan towards the Late Holocene[4]. Since this location is not far from the intertidal area, marine influence was also observed because of higher frequency of foraminiferal remains.

The Kerala basin provides a better representation of the NPP, and in one of the bore holes (Pachha) they are better preserved than that of pollen and spores. Here both algal and terrestrial remains occur in abundance. *Botryo-*

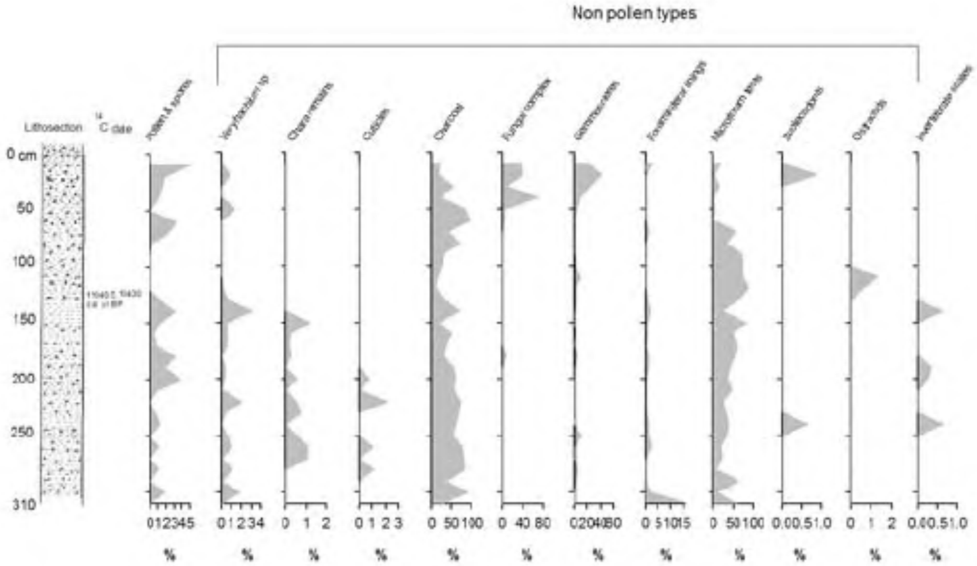

Figure 4. NPP and pollen profile of Navlakhi (Gujarat), India.

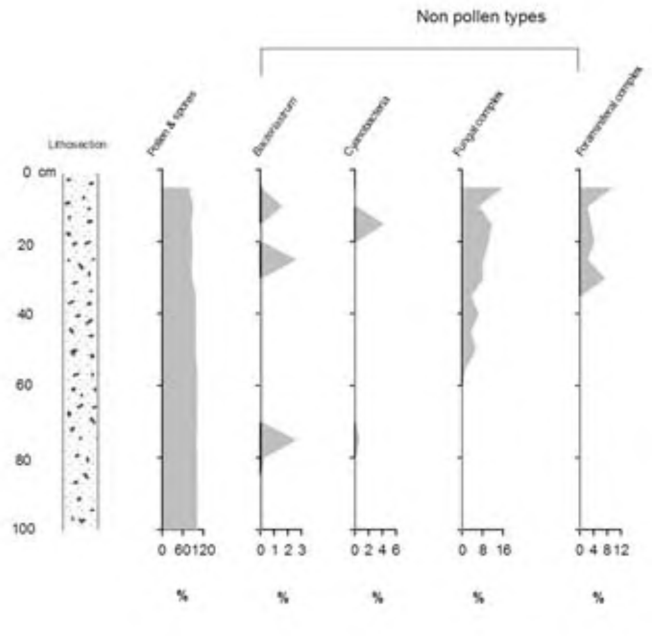

Figure 5. NPP and pollen profile of Aravi (Konkan), India.

coccus, cyanobacteria, thecamoeba, microscopic charcoal, fungal complex, foraminiferal linings, etc. are well represented at different levels. Presence of fungal complex along with pollen and spores at higher levels of the profile, suggests humid and wet conditions in the Late Holocene along the southwest coast of India. On the contrary, heavy accumulation of charcoal remains and poor turnover of pollen and spores and fungal remains may be attributed to relatively dry and less humid period, and prevalence of forest fire-related events. Dominance of *Botryococcus*, a freshwater alga only at 2 m level indicates a dry period in the Late Holocene, which is equally supported by the thecamoebians as they are found usually in stressed environment. A similar scenario was present at Lothal, where abundance of thecamoebians was observed by Khadkikar *et al.*[14].

From the above case studies, it has been observed that the NPP have good potential as palaeoenvironmental indicators in the Late Quaternary studies of the west coast of India. Since these organic remains have not been given due consideration, there is scope to utilize them for palaeoecological and palaeoclimate study. Freshwater algae, *Botryococcus* and *Pediastrum* are frequently encountered in the Holocene lagoonal deposits of the Kerala basin and their relative abundance in the profile suggests oscillations in atmospheric precipitation. They may serve as sensitive indicators of salinity, pH and depth changes in palaeolagoons influenced by sea-level oscillations and climate. Higher concentration of *Botryococcus* in the lagoonal deposits may be attributed to dry periods, whereas increase in *Pediastrum* may indicate wet periods[60,61]. Higher frequency of microscopic charcoal in the preparations indicates forest fire-related events as a result of prevailing dry periods. Such inferences of local-scale fire episodes have already been made while reconstructing the fire history of sub-arctic lake sediments[62]. Further, it may also reveal a period of human-induced forest clearance and burning to obtain openings for cultivation that might have led to significant deduction in forest vegetation, particularly in the tropics. However, this aspect has not been addressed while assessing relative importance of climate change and of pre-human impact for the Holocene along the west coast of India. The presence of remains of *Chara*, a green alga in the deposits at certain levels in the stratigraphic column may be associated with seasonal precipi-

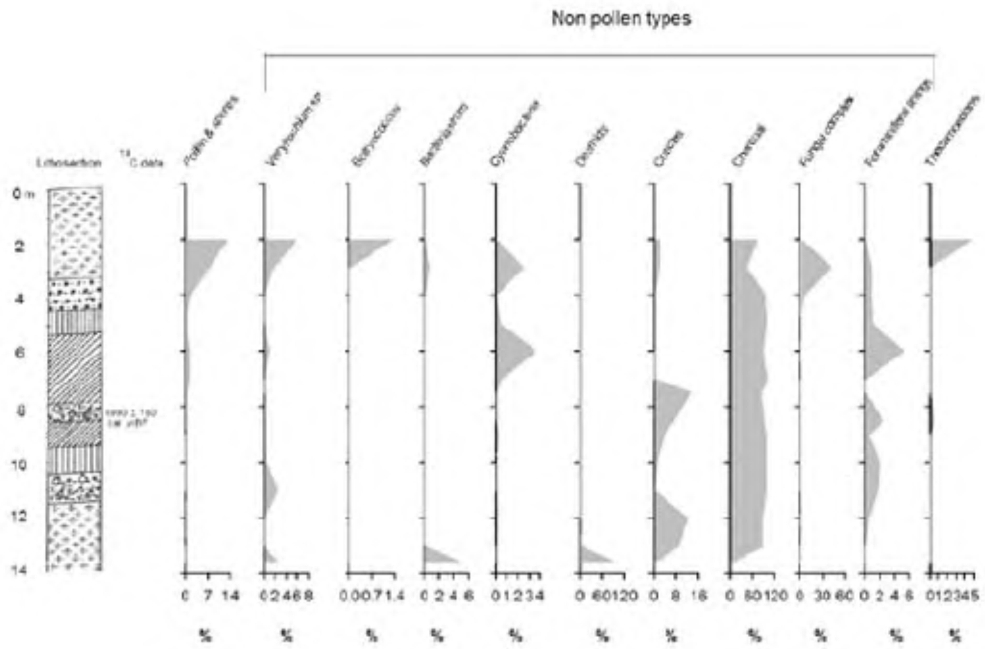

Figure 6. NPP and pollen profile of Pachha (Kerala), India.

tation along the west coast. Thus, the NPP data so far derived demonstrated good potential for palaeoecological consideration and to interpret the palaeoclimate changes during the Late Quaternary of the west coast of India.

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