

Palynological record of tropical rain forest vegetation and sea level fluctuations since 140 ka from sediment core, south-eastern Arabian Sea

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Abstract

Palyno-chronological study of a 552 cm deep sediment core from the south-eastern Arabian Sea covers a time span of ~140 ka. The age estimate is based on oxygen isotopic data of planktic foraminifera. Six zones were identified on the basis of palynology covering partially MIS-6 and MIS-5 to MIS-1 (Marine Isotopic Stages). The interglacial period (MIS-5) shows high rate of sedimentation corresponding to high percentage of terrestrial rain forest pollen. The palynological study reveals highstand and intense rain forest vegetation during MIS 5a which corresponds to the similar earlier records of estuarine ecosystem on land in Kerala. The relative sea level rise and fall since ~140 ka have been inferred through quantitative estimate of marine versus terrestrial palynomorphs. The terrigenous non-pollen forms comprised abundant Neogene extinct nanoplanktons (*Discoaster* spp.) until MIS-3 which was transported from the Varkala Formation (highlands of the Kerala coast). The pollen assemblage is comparable to the present day flora in Kerala except *Ongokea* goro which is now present in South Africa and therefore, the provenance of pollen recorded in the studied core is Western Ghats of India. High percentage of planktic foraminifera and dinoflagellate cysts throughout the core indicates high productivity that suggests upwelling induced by seasonal reversals in the monsoon winds even during the glacial periods. *Botryococcus* remains and poaceous leaf cuticles dominated by the *Pooideae* group in the marine realm also point towards active winter monsoon. Considerable fragmentation of rain forest took place post 74 ka and during the LGM as the sea retreated to its maximum which resulted into the vast exposure of land favoring the expanse of grassland with pockets of rain forest “plant refugia” on land. Neogene rain forest flora recorded earlier from the Varkala Formation and the present record of its existence since MIS-6 in the region provide an understanding that the monsoon circulation over southern India was similar since the Middle Miocene Climate Optimum and the flora in the South-Western Ghats is a fossil ecosystem and a relic of the Tertiary period.

1. Introduction

The emergence of the rain forest ecosystem (Corlett and Primack, 2006) and its diversification in the Late Cretaceous and Early Paleogene during the movement of the Indian Plate from southern to midlatitudes, in response to changes in the global climate pattern, have been reported earlier (Givinish, 1999). Later, the Quaternary period witnessed the most dynamic climatic conditions (Morley, 2000), leading to a situation in which extinction of plants was more important than speciation. This time scale exhibits a dramatic biogeographic shift in vegetation forced by climate change (Huntley and Webb, 1989). It has been seen that the diversity of trees is the highest in those tropical regions where climate has varied the least during various geological periods and the lowest in those areas where tropical forests were most disrupted by the cyclic revolutions of climate, especially during the Pleistocene (Morley, 2000). The South-Western Ghats is a home to endemic rain forest diversity due to highest rainfall in the region (Pascal, 1982). The climatic fluctuation during the Quaternary period played an important role in defining the vegetation and sea-level changes. The magnitude of terrigenous input in the marine sediment is often controlled by fluvial/aeolian processes. Major changes in the monsoon cycle since the last interglacial period have been studied through palynology in marine sediments from the Arabian Sea (Van Campo et al., 1982; Van Campo, 1986) and since ~200 ka (Prabhu et al., 2004) and from off the northwest African coast (Hooghiemstra, 1988). Repeated cycles of glacial and interglacial conditions of high magnitude and longer duration largely affected the vegetation. The primary source of vegetation evidences is fossil pollen records preserved in natural archives. Earlier, it has been recorded that the present day endemic flora in South-Western Ghats, India, is the legacy of Paleogene/Neogene flora that survived as 'refugia' during the Quaternary glacial periods (Prasad et al., 2009; Farooqui et al., 2010). During these periods, the process of migration and colonization of the vegetation and its sustenance eventually led to several species extinctions or additions. There is a wide gap in the knowledge of vegetational changes that might have occurred during the subsequent Quaternary period. Pleistocene glacial/interglacial sedimentary deposits in the marine realm and in the Indian sub-continent depicting vegetation status are rare which do not provide complete answers to their lineage and relationship with the climate change through time.

Existing paleoceanographic studies for the southeastern Arabian Sea are confined to productivity variations, terrigenous inputs and redox conditions during the past 140 ka (Pattan et al., 2003, 2005; Pattan and Pearce, 2009). The present study provides insight into the effect that the Quaternary climate had on the rain forest vegetation in the Indian Peninsula. The main objectives of this paper are (1) to document the record of the Western Ghats rain forest flora during the Pleistocene interglacial/glacial cycles, (2) to correlate the terrigenous input with the sea level changes along the west coast of India and (3) to elucidate the endemism (legacy) of rain forest vegetation in South-Western Ghats.

1.1. Modern vegetation in close proximity to studied site

The southern part of the west coast of the Indian Peninsula situated towards east of the studied core is one of the hotspots of endemic rain forest diversity (Fig. 1). The rain forests of the Western

Ghats are more diverse, with over 4000 plant species occurring in this relatively small area of hilly terrain. Of these, 1800 species are confined to southernmost forests of the Western Ghats (covering major part in Kerala and adjoining Tamil Nadu border), experiencing the highest rainfall per annum. More than 56% of the trees are monotypic and endemic evergreen rain forest existing between 8° and 11° latitudes (Ramesh and Pascal, 1997; Barboni et al., 2003). The floral diversity of this region in relation to climate has been a subject of extensive study (Pascal, 1982,

1986, 1988, 1991; Ganesh et al., 1996; Ghate et al., 1998; Bonnefille et al., 1999; Barboni and Bonnefille, 2001; Barboni et al., 2003).

The studied site is closer to Lakshadweep islands (off west coast, India) and the present day flora reported from the area (Prain, 1894; Gardiner, 1906) comprises *Moringa oleifera*, *Artocarpus altilis*, *Terminalia catappa*, *Scaevola sericea*, *Premna obtusifolia*, *Calophyllum inophyllum*, *Pandanus odoratissimus*, *Morinda citrifolia*, etc. Trees like *Casuarina equisetifolia*, *Ziziphus mauritiana* and *Thespesia populnea* are also seen growing wild. *Musa paradisiaca*, *Colocasia esculenta*, *Carica papaya*, *Amaranthus* sp., etc., are cultivated here. Therefore, the provenance of the terrigenous sediment in the studied marine realm is likely to be largely from the western coast of India and Lakshadweep islands either through fluvial or aeolian process.

1.2. Past vegetation from the west coast and Arabian Sea

The Tertiary deposits (Varkala Formation) along the south west coast of India reveal pollen assemblage that comprises about 49 taxa belonging to 43 families. All these species are at present distributed in the tropical Indo-West Pacific region. The Varkala pollen flora indicates a seasonal precipitation pattern with a dry and a wet period and moderate rainfalls during the warmest period (Ramanujam, 1987). Short-term paleoclimatic records for the Late Quaternary glacial and interglacial periods based on pollen studies are meager from the eastern Arabian Sea (Van Campo et al., 1982; Caratini et al., 1994; Bentaleb et al., 1997) and Kerala (Narayanan et al., 2002; Kumaran et al., 2008). However, the Pleistocene interglacial period around 80 ka shows considerable account of evergreen pollen taxa from the Arabian Sea (Prabhu et al., 2004) and on land from Kerala (Vasanthy, 1988; Farooqui et al., 2010). Similar studies from the Palni Hills have revealed the presence of tropical rain forest since the Late Pleistocene (Bera et al., 1997; Bera and Farooqui, 2000).

Pollen record of the Tropical Montane Forest from lake sediments in the Anaimalai and Nilgiri Hills in the South-Western Ghats has also been documented for Holocene (Vishnu-Mittre and Gupta, 1971; Blasco and Thanikaimoni, 1974; Vasanthy, 1988; Gupta and Bera, 1996). These palynochronological studies show that evergreen to semi-evergreen rain forest dominated in the middle Holocene epoch, but the Last Glacial Maxima (LGM) was largely represented by savanna grassland.

1.3. Geographical position, climate and geology of the study area

The Arabian Sea, the north-eastern part of the Indian Ocean, is bounded to the west mainly by the Arabian Peninsula, to the north by countries like Iran and Pakistan, to the east by the Indian Peninsula and to the south by the Indian Ocean. The climate and surface water oceanography of the Arabian Sea region are dominated by south-west monsoon winds and the retreating north-east winds. These winds induce a lot of upwelling in the Arabian Seawaters that triggers spectacular phytoplankton blooms, resulting in the region being one of the most productive areas of the world oceans (Qasim, 1982). A stable, mid depth oxygen minimum zone (OMZ) at 200–1200 m water depth prevails in the Arabian Sea due to high fluxes of both wind and river transported terrestrial sediment and high oceanic (monsoonal) surface-water productivity and biogenic fluxes. Paleoclimatic studies have shown that the intensity of the monsoon varied through time. During the Last Glacial Maximum the summer monsoon was weaker (Prell et al., 1980; Duplessy, 1982), and the winter monsoon was stronger (Duplessy, 1982; Fontugne and Duplessy, 1986; Sarkar et al., 1990). The summer monsoon variability is recorded (Beaufort, 1996) particularly well in the Arabian Sea where the strongest wind appears during summer (Knox, 1987). The variation in intensity of the winter monsoon induces fluctuations in productivity (Beaufort, 1996). A general high frequency instability of Late Pleistocene climate from the northeastern Arabian Sea and Greenland has been recorded on timescales of few millennium, centuries to decades (Schulz et al., 1998). However, the records of Pleistocene climate change from the southern Arabian Sea is yet unexplored.

The Kerala–Konkan basin situated south of east–west trending Vengurla Arch extends up to Cape Comorin in the south of the Indian sub-continent and lies in between the western (older than 0.84 Ma (OTT)) offshore basin. These Mio-Pliocene sedimentary rocks are fairly widespread in the southern coastal belt (CGWB, 1992) and their remnants are noticeable in the central and northern coastal areas. The basin continues into deep-waters to the Chagos–Laccadive Ridge (Shankar et al., 2004; Narayanan et al., 2007; Campanile et al., 2008). The Chagos–Laccadive Ridge is supposed to be the continuation of the Aravalli mountains. The Laccadive archipelago consists of about 20 islands and is separated from the Indian Peninsula between latitude 8° and 12°30'N and longitude 71° and 74°E at a distance ranging from 200 km to 400 km covering a 290 km sea stretch from Kochi — the mainland of the Kerala coast. The studied core sediment is located (9°21'N latitude, 71°59'E Longitude) in the pericratonic Konkan–Kerala Basin on the Western Indian passive continental margin (Figs. 1 and 2). The Tertiary formation of the Kerala coast is divided into four distinct beds viz. Alleppey, Vaikom, Quilon and Varkala (CGWB, 1992). The Varkala Formation was deposited during the Late Miocene to Pliocene under extremely shallow marine to inner neritic environment which is the only place in southern Kerala where cliffs are found adjacent to the Arabian Sea (Vaidyanadhan and Ramakrishnan, 2008; Reuter et al., 2010). These are about 20 m thick series of sedimentary rocks. Here, the variegated clay and sandstones with lenticular seams of lignite are underlain by more compact marly sands with shell fragments and thin horizons of limestone that are known as the Quilon Formation. The age assigned to the Quilon Formation is Oligocene to Middle Miocene where two horizons of limestone reveal fossiliferous marine fauna constituting *Discoaster* spp. and other marine nanoplanktons (Menon, 1967; Reuter et al., 2010).

Lakshadweep Depression is situated between the continental shelf and the Laccadive Ridge and is almost completely outlined by 1900 m isobaths (Fig. 2). The width of the depression gradually decreases from approximately 215 km in the south to approximately 70–65 km in the north. The total thickness of sediments varies from 200 to 3200 m reaching a maximum about 5500 m at places. This depression displays no sign of its spreading and is probably underlain by a stretched continental or volcanic crust. The present sediment core is of the late Quaternary in age but rich Neogene nanoplankton assemblages reveal the provenance of terrigenous matter from the abovementioned nearby/adjacent west coast of the Indian sub-continent.

2. Materials and method

A 552 cm long gravity sediment core (SK-129/CR-05) was collected from the south-eastern Arabian Sea (Figs. 1 and 2) at a water depth of 2300 m and at 9°21'N latitude; 71°59'E longitude. The sediment core was sub-sampled at 2 cm interval on board ORV Sagar Kanya. The age model for the studied sediment core (Pattan et al., 2003) is based on the oxygen isotope record of planktic foraminifera *Globigerinoides ruber* (size range of 250–350 μm). The Marine Isotopic Stages (MIS) 1–6 and corresponding time period given in kilo yrs (ka) have been categorized according to Wright (2000). This core covers a time span of ~140 ka from Marine Isotope Stage-6 to the Present. For palynological study, the sediments were chemically processed using the standard acetolysis method (Erdtman, 1943) and pollen grains were counted and identified in 10 g of each sub-sample at 2 cm interval of the entire core. Plant elements (pollen/spore forms — PFs) in the study have been categorized into arboreal, mangroves, evergreen/semi-evergreen (trees), and non-arboreals (terrestrial herbs and marshy/aquatics). Fungal remains were excluded from total count as these were recorded in very low number only in Phase 1. The non-pollen forms (NPFs) recorded here in the palynological slides are poaceous cuticular fragments (showing bilobed, short celled and crossed or rondel shape phytolith cells), phytolith, algae — mainly as *Botryococcus* remains, dinoflagellate cysts, organic linings of foraminifers and nanoplanktons. The phytolith study through recommended methodology is under progress and will be published separately. For the precise identification of fossil palynomorphs in the sediments, the reference pollen slides available at BSIP Herbarium as well as the pollen photographs in the published literature (Vasanthi, 1988; Nayar, 1990; Tissot et al., 1994; Farooqui et al., 2010; Demske et al., 2012) were consulted and photo documentation of PFs and NPFs were done using Olympus BX-51TF Microscope. Aubry (1985) and Lambert (2003) were referred for identification of nanoplanktons. The NPFs represent the percentage of the total pollen count which provides here a supporting proxy in order to understand the provenance and magnitude of the sediment input. The NPFs were quantified in order to understand the extent of marine versus terrestrial clastics deposited in succession to identify the source of organic matter and weighting the relative importance of fluvial and authigenic inputs in relation to relative sea level fluctuations. The graph spectrum of PFs and NPFs was made using Microsoft excel and later edited in CorelDraw-12. The rate of sedimentation was calculated using depth versus oxygen isotopic age. The sediment composition of the core exhibits the presence of clay, silt and organic matter in invariable fraction (Pattan et al., 2003). The depth-wise lithological details of the core are given in Table 1. The South-Western Ghats Montane forest representing the vegetation in the present day wet climatic

conditions formed a key to infer the past vegetational evolution through palynological study. Palynological study and data compilation were carried out in BSIP and sample collection, Isotopic Age determination of the sediment core in National Institute of Oceanography (NIO).

3. Results

3.1. Sedimentation and chronology

The lithology of the sediment core is provided in Table 1. Throughout the core, the sediment is blackish, silty and clayey silt. The average rate of sedimentation calculated using oxygen isotopic age data was comparatively higher during MIS-5 and 4. The highest peak (11.3 cm/ka) is recorded during the early phase of MIS-3 (Fig. 3). However, the latter part of MIS-3 and 2 shows low rate of sedimentation (~3.8 cm/ka). The average net rate of sedimentation during MIS 2 & 1 shows 5.0 cm/ka. Overall, high fluctuation in the sedimentation rate is recorded during MIS-3 (early phase), 4 and 5. The linear interpolation between the oxygen isotope stage boundaries reveals variations in sedimentation rates between 3.67 and 5.20 cm/ka (average of 4.14 cm/ka), with highest sedimentation (5.2 cm/ka) during MIS-4 (Pattan et al., 2005). During MIS-5, sedimentation rates varied from 0.8 to 7 cm/ka. MIS-6 period shows an incomplete record because the time period extends very much beyond the core length. With exceptions mentioned above, the rate of sedimentation during MIS-5 was maximum (Fig. 5) followed by MIS-3 and 1 on the basis of time span assigned to these Interglacial Stages. MIS-4 shows an increase in sedimentation as compared to MIS-2 and MIS-6 (incomplete record). The high rate of sedimentation recorded during the interglacial periods also coincides with the abundance of high percentage of terrestrial pollen assemblage. The relative sea level rise and fall as inferred through quantitative marine versus terrestrial palynomorphs show the highest sea level stand during MIS-5.

3.2. Palynology

The source/provenance of most part of the terrestrial organic matter buried in the sediment core is largely from the south-western part of Indian subcontinent. Therefore, the reconstruction of the vegetation since ~140 ka through palynology (Figs. 4 and 5) is understood to reflect the vegetational evolution in the vicinity on land and in situ oceanic productivity. The PF's and NPF's assemblages in the studied core were grouped into Zones 1–6 corresponding to MIS-6 to MIS-1 in order to understand the impact of the Quaternary glacial and interglacial cycles that directly or indirectly had on vegetation evolution and sea level fluctuations in the region.

3.2.1. Zone-1; 141–130 ka (MIS-6)

The total organic matter assemblage shows abundance of Foraminifera linings (41.7%) followed by Botryococcus (22%), poaceous cuticular fragments (18.5%) and dinoflagellate cysts (8.5%) dominated by Nematospaeropsis. The pollen grains and phytoliths (Figs. 6 & 8) show an average of 5.1% and 4.2% of the total count, respectively. Thus, the organic matter derived from terrestrial plants constitutes 49.8% and the marine forms constitute about 50.2% of the total PF's and NPF's count. The

pollen assemblage during this period comprises *Aglaia simplicifolia*, *Dipterocarpus*, *Dysoxylum*, *Myristica*, *Meliaceae*, *Moraceae*, and *Poaceae/Cyperaceae* (Fig. 7).

3.2.2. Zone 2; 129–75 ka (MIS-5)

Absence of pollen and very low percentage of poaceous cuticular fragments (13.1) were recorded between the 129 and 119 ka (MIS-5e) period (Figs. 6 and 7). High percentage of Foraminifera organic linings (44.3%), *Botryococcus* (38.9%) and phytolith constituting 3.7% was recorded during this period.

The marine palynomorphs constitute an average of 45.8% of the total count between 119 and 94 ka (MIS-5c & 5d) interval constituting Foraminifera linings and dinoflagellate cysts (Fig. 9). *Nematosphaeropsis* (14%) along with the *Spiniferites* species (9.3%) together constitute 23.3%. *Nematosphaeropsis* increase in percentage during ~100 to 118 ka. The poaceous cuticular fragments (Fig. 8) show abundance (26.1%). This is followed by 15.5% of *Botryococcus*, 5.7% of pollen and 0.7% of phytolith. Reworked nanoplanktons constituting species of extinct *Discoaster* spp. and *Amaurolithus* show ~29–33% of the total count only during MIS-5d. During MIS-5c and 5d the nanoplanktons constitute an average of 6.2%. Thus, the total constituent of the terrestrial organic matter is 54.2% and the rest constitute the marine forms. The pollen grains recorded (Fig. 7) are of Mangroves (*Rhizophora*, *Sonneratia*), *Anacardium*, *Aglaia simplicifolia*, *Bignoniaceae*, *Chrysophyllum*, *Dipterocarpaceae*, *Dysoxylum malabaricum*, *Dysoxylum buxifolia*, *Garuga pinnata*, *Humboldtia*, *Limonia* type, *Luvunga*, *Meliaceae*, *Moraceae*, *Myristica malabarica*, *Nothopegia travancorica*, *Palaquium*, *Arecaceae*, *Rosaceae*, *Rutaceae*, *Sapotaceae*, *Semecarpus*, *Solanaceae*, *Terminalia*, *Mallotus beddomei*, *Asteraceae*, *Liliaceae*, and *Poaceae/Cyperaceae*. All these pollen grains represent less than 0.5% of the total count. A very high percentage (33.1%) of *Discoaster* spp. and *Amaurolithus* was recorded between 94 and 88 ka (MIS-5b). The Foraminifera organic linings constitute ~25.9% followed by *Nematosphaeropsis* (6.1%) and *Spiniferites* (5.7%). The total terrigenous matter amounts to about 62.3% and in situ marine forms amount to ~37.7%. The constituents of terrestrial origin are *Botryococcus* (18.9%), poaceous cuticular fragments (8.3%), pollen (1.7%) and phytolith (0.4%) along with a high percentage of Neogene nanoplanktons. Between 88 and 75 ka (MIS-5a) the total terrestrial organic matter assemblage is highest and the percentage of poaceous cuticular fragments (dominated by dumbbell-shaped phytoliths and rare occurrence of crossed or rondel-shaped) is 19.2% followed by *Botryococcus* (13.8%), pollen/spores (12.2%), grass phytolith (8.3%) and reworked nanoplanktons (8.0%). Among the marine forms *Nematosphaeropsis* accounts for 17.0% of the total organic matter count. This was followed by Foraminifera linings (16.6%) and *Spiniferites* (4.9%). However, a sudden increase in *Nematosphaeropsis labyrinthica* along with *Tuberculodinium vancampoae* was observed along with a good number of pollen during this period. The pollen grains mainly represent rainforest vegetation along with the mangroves between 87 and 75 ka (Figs. 5 & 7). Mangroves (*Excoecaria*, *Rhizophora*, *Sonneratia*) comprise an average percentage of 1.2 (Fig. 5), *Anacardium* (14.5), *Aglaia simplicifolia* (2.9), *Agrostistachys* (1.4), *Bignoniaceae* (1.2), *Chrysophyllum* (5.3), *Dipterocarpaceae* (2.7), *Dysoxylum malabaricum* (0.9), *Dysoxylum buxifolia* (2.2), *Garuga pinnata* (3.0), *Gnetum* (0.1), *Hopea* (0.4), *Humboldtia* (0.8), *Limonia* type (12.4), *Luvunga* (0.1), *Meliaceae* (10.6), *Moraceae* (4.4),

Myristica malabarica (4.4), *Nothopegia travancorica* (1.8), *Ongokea* (0.8), *Palaquium* (0.8), *Arecaceae* (2.5), *Pinus* (0.3), *Psychotria annamalayana* (0.4), *Psychotria flavida* type (0.1), *Rosaceae*, *Reinwardtiidendron* (0.2), *Prunus* type? (3.0), *Rutaceae* (3.9), *Sapotaceae* (17.2), *Sauropus androgynus* (0.4), *Semecarpus* (0.4), *Solanaceae* (0.4), *Terminalia* (4.7), *Tiliaceae* (0.7), *Walsura* (0.8), *Clerodendrum* (0.1), *Mallotus beddomei* (1.6), *Murraya paniculata* (0.1), *Violaceae* (0.2), *Artemisia* (0.2), *Asteraceae* (0.6), *Justicia* (1.0), *Liliaceae* (0.3) and *Poaceae/Cyperaceae* (16.2).

3.2.3. Zone-3; 75–59 ka (MIS-4)

The highest percentage (36.2) was of reworked nanoplanktons dominated by extinct *Discoaster* spp. and *Amaurolithus* in association with fresh water algae *Botryococcus* (17.6%). About 5 species of *Discoaster* and 3 species of *Amaurolithus* were identified (Fig. 9). The poaceous cuticular fragments (dominated by dumbbell-shaped and short-celled phytoliths; Fig. 8), pollen/spores and phytolith constitute 8.4%, 2.8% and 8.0%, respectively. The pollen grains were abundant only during 75–73 ka (Fig. 5). These constitute *Agrostistachys* (2.9%), *Anacardium* (13.5%), *Aglaia* (2.9%), *Chrysophyllum*, *Dipterocarpaceae*, *Garuga*, *Hopea* (6–8%), *Meliaceae* (16.5%), *Nothopegia*, *Rutaceae*, *Sapotaceae*, and *Solanaceae* (4–6%). *Poaceae* and *Cyperaceae* increase in percentage (16.7%). Out of these the pollen of *Meliaceae* and *Poaceae* increases in percentage. After this period, the stray occurrence of pollen grains was recorded. Foraminifera linings show 25.4% followed by 1.6% of *Spiniferites*. During this period absence of *Nematosphaeropsis* was observed.

3.2.4. Zone-4; 59–24 ka (MIS-3)

The terrestrial input in the sediment was 25.1% which constituted poaceous cuticular fragments (dominated by dumbbell-shaped and short-celled phytoliths) followed by *Botryococcus*, reworked *Discoaster* spp., pollen and phytolith constituting 12.7%, 8.6%, 1.6% and 0.7%, respectively. However, *Botryococcus* shows its abundance only between 59–51 ka and 38–25 ka. During 51–38 ka complete absence of *Botryococcus* is observed. The terrestrial forms constitute 48.9% and the rest 51.1% constitute marine forms out of the total count. During 59–51 ka the abundance of *Discoaster* spp. is similar to that of *Botryococcus* and foraminifers. Pollen percentage is low (Figs. 4 & 6) and could not be counted for quantitative analysis. Poaceous cuticles dominated by the *Pooideae* sub-family show high percentage of the total biotic remains. *Discoaster* spp. and *Botryococcus* were absent during 51–38 ka. Although the pollen count remained negligible (Fig. 4) both benthic and planktic foraminifera linings show abundance. The

period from ~38–30 ka again shows a good percentage of Neogene nanoplankton assemblage along with a high frequency of *Botryococcus*, Foraminifera lining and poaceous cuticle. Pollen count is negligible with stray appearance of *Poaceae* and *Chenopodiaceae/Amaranthaceae*. During 30–24 ka *Botryococcus* was abundant and in association with foraminifera followed by poaceous cuticle (dominated by short-celled phytoliths Fig. 8) and low pollen counts (Fig. 4). Pollen record of nonarborescens such as *Chenopodiaceae/Amaranthaceae*, *Caryophyllaceae*, *Campanulaceae* was recorded. *Poaceae* and *Cyperaceae* also show rare presence.

3.2.5. Zone-5; 12–24 ka (MIS-2)

The poaceous cuticular fragments constitute 34.8% (dominated by short-celled phytoliths followed by dumbbell-shaped phytoliths) followed by low occurrence of pollen (3.9%), Botryococcus (3.1%) and phytolith (2.9%). At ~18 ka, an abrupt high peak (30.7%) of Botryococcus was recorded. The reworked Neogene nanoplanktons were observed in low percentage (3%) during this period. Among the marine forms, the Foraminifera organic linings (38.9%) and Spiniferites (13.4%) show high percentage. Nematosphaeropsis were not recorded. Thus, the total terrestrial input was 47.7% and the marine forms were 52.3%. This zone shows stray occurrence of pollen grains belonging to families Chenopodiaceae/Amaranthaceae etc.

3.2.6. Zone-6; 0–12 ka (MIS-1)

This zone is characterized by a high percentage of poaceous cuticles (29%) that were burnt, microscopic charcoal type of organic debris (Fig. 8). Total planktic and benthic foraminifera linings were high (47.4%). The Spiniferites dinoflagellate cysts show a comparatively high percentage (9.2%). The pollen, phytolith, and Botryococcus show low percentage constituting 8.7%, 2.4% and 3.2%, respectively. Total terrestrial palynomorphs constitute 43.3% and marine forms constitute 56.7%. Although the pollen count was low, the diversity of herbaceous plant species was recorded in the assemblage along with few arboreals. These include pollen (Fig. 4) of Poaceae/Cyperaceae, Chenopodiaceae/Amaranthaceae, Caryophyllaceae, Campanulaceae, Asteraceae, Artemisia, Urticaceae, Fabaceae, Liliaceae, Meliaceae, Lophopetalum wallichianum, Chlorophytum and Pinus.

4. Discussion

The rate of sediment deposition in the study site was greatly influenced by a series of climate change during the Quaternary period since ~140 ka which defined the status of mangroves and the rain forest vegetation in the provenance, i.e., west coast, India. The vegetation on land as well as in wetland/oceanic productivity in general recorded through palynological study shows equilibrium with the prevailing climate during the glacial and interglacial cycles since ~140 ka. South-Western Ghat forest (Shola forest) is a unique montane vegetation occupying temperate habitats in tropical latitude. The relics of an ecoclimatic and geologic past are preserved in its pristine form at least in certain parts of these mist laden canopies of the mountains and have been described as fossil rain forest ecosystem.

During MIS 6 (141–130 ka) out of 5.1% only stray occurrences (4.6%) of pollen belonging to Sapotaceae, Meliaceae, Dipterocarpaceae, Myristicaceae, Moraceae and Rutaceae indicate an occurrence of rain forest in the vicinity. The other remaining 0.5% were of Poaceae/Cyperaceae. The black (charcoal type) poaceous cuticular fragments having dumbbell-shaped and short-celled silica cells were quite common throughout the studied core but dominate during MIS-5. The dumbbell (lobate) shape phytoliths in general originate from the epidermal cells of Panicoideae and Oryzoideae, some Arundinoideae and Chloridoideae subfamilies (Twiss et al., 1969; Mulholland, 1989; Lu and Liu, 2003). These bilobates/dumbbell phytolith cells are dominant in C4 grasses which thrive in warm climatic

conditions where soil moisture is high. However, short-celled phytolith cells were also recorded in increased percentage during the glacial periods. The high percentage of poaceous cuticular fragments and *Botryococcus* remains indicates the proximity to continental wetland. Enhanced percentage of planktic foraminifera followed by dinoflagellate cysts shows increased oceanic productivity. *Nematosphaeropsis labyrinthea* and *Tuberculodinium vancampoae* were relatively present in abundance as compared to *Spiniferites* during MIS-5. *Nematosphaeropsis labyrinthea* has an outer neritic/oceanic distribution in tropical to temperate deep ocean (Wall et al., 1977; Harland, 1983). Thus, the site of studied core was quite off-shore indicating greater distance from the shoreline during MIS-5.

The present study reveals an occurrence of *Nematosphaeropsis labyrinthea* and *Tuberculodinium vancampoae* only up to 77 ka. Later, in succession towards younger periods these dinoflagellate cysts were not recorded. Thus, the glacial periods post Youngest Toba Tuff (YTT) might have directly or indirectly affected its population responding to either shoreline retreat or climate change. It has been recorded that *N. labyrinthea* is known to have decreased during the past 1000 years (Edwards and Anderle, 1992).

The abundance and diversity of rain forest pollen assemblage comparable to the present day South-Western Ghats flora of peninsular India were recorded during MIS-5a. This indicates that the precipitation pattern and monsoon system were similar or more intense than the present conditions prevailing in South-Western Ghats. High percentage of the pollen belonging to family Meliaceae followed by Sapotaceae, Anacardiaceae, Combretaceae, Moraceae, Myristicaceae, Myrsinaceae, Myrtaceae, Symplocaceae, Dipterocarpaceae, Rosaceae, Rutaceae, Lauraceae and Bignoniaceae was recorded. Rare occurrence (0.8%) of *Ongokea gore* (Olacaceae) is also recorded here for the first time and is likely to be one of the associates of the then existing rain forest in Western Ghats. At present this species is absent from the rain forests of India. The known origin and geographic distribution of *O. gore* as of today are Sierra Leone, eastern DR Congo and Angola which provides clue to probable Gondwana lineage of the rain forest in India. It is scattered here in dense evergreen or moist deciduous forest. Since the germination of its seed is slow and irregular taking several months or even more than a year, it is likely that it could not survive the severity of the Quaternary glacial period post YTT event in the Indian subcontinent.

About 80 pollen taxa have been reported earlier from sediments of two well sections from Changanacherry (25 km from the present Alleppey coastline and near Vembanad lake), Kerala. The pollen assemblage comprises 78% of the evergreen and moist deciduous taxa along with the mangrove pollen and a good percentage of marine dinoflagellate cysts indicating estuarine ecosystem during MIS 5a in Changanacherry (Farooqui et al., 2010). During this period (MIS 5a) abundance and diversity of pollen assemblage were also recorded in the present studied core which reveals firstly, that the South-Western Ghats had dense evergreen rain forest vegetation both in hilly montane areas and in riparian forest along the rivers providing polleniferous terrigenous matter in the marine realm. Secondly, the climate prior to YTT event was quite warm and humid with high precipitation and low seasonality and the shoreline was much beyond the present day shoreline in the Kerala coast during MIS 5a. Thus, the

estuarine ecosystem recorded in Changanacherry corresponds to the global sea level highstand during MIS-5a around 80 ka (Fairbanks and Matthews, 1978; Toscano and Lundberg, 1999; Shackleton et al., 2000). During the highstand (MIS 5a) the pollen assemblage of rain forest was also high in marine sediment. Thus, it is inferred that the terrigenous pollen assemblage is likely to be high in marine sediment during highstands when the provenance is near the shoreline or in other words the magnitude of terrigenous input in marine realms directly proportional to the high sea level. Fig. 5 shows that during the late MIS-6 and the entire MIS-5 the relative sea level was high and closer to the present day shoreline on the basis of percentage of marine versus terrestrial palynomorphs. The mangroves harbored the coastal wetland during MIS-6 & 5 and exist at present along the Kerala coastline that reached its present position during Holocene transgression.

The terrigenous input and its preservation in the marine realm were influenced by two major factors. Firstly, the magnitude of fluvial and aeolian activity during the glacial and interglacial cycles and secondly, the oxic to sub-oxic bottom conditions. The bottom water oxygenation history since 140 ka in the same core (SK-129 CR05) has been studied by Pattan and Pearce (2009). The concentrations of multiple redox sensitive elements reveal that the Last Glacial Maxima (17.48 ka), stadials of Marine Isotope Stage (MIS)-5 (5b and 5d) and Glacial Termination (GT)-II (133 ka) were associated with suboxic bottom water conditions. Marine Isotope Stages 1, 3, 4 and interstadials of MIS-5 (5a, 5c & 5e) were all associated with near oxic conditions. However, fairly excellent preservation of pollen, spores, and other non-pollen terrestrial forms along with the marine palynomorphs does not correlate well with the oxic conditions during these periods. It could be because the rate of chemical oxygen demand (COD) is generally higher than biological oxygen demand (BOD) and therefore, it is likely that the particulate organic matter such as palynomorphs could have escaped oxidation.

The pollen assemblage reduced in diversity as well as in percentage in ascending sequence from MIS-4 to 1. However, abundant *Botryococcus* remains, phytolith, poaceous cuticles as well as nanoplanktons like *Discoaster* spp. and *Amaurolithus* continued throughout until MIS-2 (LGM). This shows a possibility of a vast exposed coastland covered by grasses, marshy areas and wetlands favoring the growth of *Botryococcus*. Therefore, it is inferred that during this period precipitation was sufficient enough which facilitated the transport of such type of terrestrial clastics into marine realm. Intermittent arid phases must have also facilitated the aeolian transport of exposed Neogene sediment cliffs in the Kerala coast. Thus, abundance of *Discoaster* spp. and *Amaurolithus* (that existed until Pliocene) in Quaternary marine sediment supports the terrigenous input from the Kerala–Konkan basin that extends up to the Kerala coast in the east of studied core. Both the glacial and interglacial cycles favored the sediment deposition influenced by aeolian and fluvial processes. Calcareous nanoplankton and planktic foraminifers are described from the marine Quilon Formation (Hardenbol et al., 1998; Kumaran et al., 2008; Piller et al., 2010; Reuter et al., 2010) of the Middle Miocene global warming (Reuter et al., 2012). The Quilon limestone is locally exposed in small outcrops at the base of sea cliffs or currently available from material dug out of wells and building excavations in the Kerala coast (Dey, 1961; Menon, 1967; Narayanan et al., 2007). The maximum thickness of Tertiary sediment are reported in and around Alleppey coastal stretch. The provenance of abundant *Discoaster* spp./*Amaurolithus* in the

studied core since MIS-6 (~140 ka) to MIS-3 (~30 ka) is thus, the south-west coast of the Indian Peninsula. The Pliocene/Pleistocene boundary for *Discoaster* spp. has been determined by Ericson et al. (1963) and Wray and Ellis (1965). Akers (1965) however, suggested that three species of *Discoaster* spp. persisted into the early Quaternary and that they became extinct between the Nebraskan glacial period and the Aftonian interglacial period. It has been reported that the productivity was higher during the glacials compared to interglacials in the eastern Arabian Sea due to convective mixing (upwelling) caused by the winter monsoon (Banakar et al., 2005; Ishfaq et al., 2013). In the present study abundance of planktic foraminifera along with Spiniferites also indicates high productivity during the glacial period suggesting nutrient availability facilitated by sediment upwelling. Convection induced by physical forcing in ocean waters and subsequently the increased biological productivity in the Arabian Sea during the north-east monsoon have been reported (Prasanna Kumar et al., 2001). As the sea retreated, the vast land was exposed during the glacial period. The winter monsoon thus facilitated the formation of a swampy area inhabited by *Botryococcus* and *Poaceae/Cyperaceae*, the remains of which were transported into the marine realm. During the glacial period the dominance of saddle, elliptical, rectangular and crossed phytoliths (Fig. 8) was recorded which are common in C3 grasses (*Pooideae* subfamily) acclimatized to cool/dry climate (Barbonie et al., 1999).

The maximum penultimate glaciations ~150 ka resulted into extended desert in North Africa (van Andel and Tzedakis, 1996). During MIS-6 the climate was drier than present and therefore, the terrestrial organic matter input along with the pollen assemblage in the present study is low. It is also inferred that because of glaciation the sea level would also have retreated from the rain forest line in the Indian subcontinent during this period. Following this, the Eemian Interglacial was interrupted by more cooler and drier phases during MIS-5b & d than at present. Similar climate has been reported from North Africa during which the rain forest occupied a far greater area than at present, and rainfall was generally higher (Frenzel et al., 1992; van Andel and Tzedakis, 1996). The MIS-5a, c & e were moist phases and palynological study reveals more dominance of the rain forest in South-Western Ghats than the present day. The schematic diagram drawn on the basis of marine versus terrestrial clastics shows that the sea level during entire MIS-5 was higher and in close proximity to rain forest vegetation on land.

The intense dry and cooler phases across North Africa or the Sahara–Arabia belt affected the northern monsoon belt too (Bond et al., 1993). Sea level was about 70 m below and information comes mainly from cores off the west coast of Africa which record pollen flux changes from the continent between 57 and 24 ka (MIS-3). Between 28 and 25 ka the climate was significantly moister than at present across Africa (Goodfriend and Margaritz, 1988; Lézine and Vergaud-Grazzini, 1994). The observations of Runge (1997) depart from the general picture where semi-arid non-forest conditions were recorded across the eastern Congo basin ~30 ka period. Our study shows either absence or very insignificant pollen assemblage but the abundance of *Botryococcus* and foraminifers indicates moister conditions during MIS-3 favoring productivity. Further, during MIS-2 and 1 the pollen record is negligible suggesting that the glacial period post YTT (cold and drier climate) was vulnerable to rain forest vegetation. Records of pollen in core sediment prior to the LGM from South-Western Ghats also show savanna grassland vegetation and absence of rain forest flora. The vegetation loss during the LGM

is apparent in the pollen spectra from core sediments (lacustrine) studied from the Palni Hills and Anaimalai Hills in South-Western Ghats (Vishnu-Mittre and Gupta, 1971; Blasco and Thanikaimoni, 1974; Vasanthy, 1988; Gupta and Bera, 1996; Rajagopalan et al., 1997). The extant tropical rain forest in the region spread across South-Western Ghats between 7 and 4 ka (Gupta, 1973; Bera et al., 1997; Bera and Farooqui, 2000). Thus, during the LGM the major part of South-Western Ghats montane (Shola) forest was represented by grassland which rejuvenated with the onset of warm and humid conditions during the middle Holocene. Considerable fragmentation of the rain forest in Southeast Asia also occurred during the LGM (Gathorne-Hardy et al., 2002). Dominance of C4 vegetation during the LGM in most of the peninsular areas in India has been reported (Sukumar et al., 1993; Meher-Homji and Gupta, 1999). It has been documented (Hooghiemstra and Van der Hammen, 1998, 2004) that the unfavorable Quaternary stadial climate cycles forced isolation of the rain forest flora into pockets as 'plant refugia' which existed as a riparian vegetation due to soil moisture availability. Such evidences of 'plant refugia' have also been reported from Africa (Plana et al., 2004). The evergreen and semi-evergreen species that generally grow on the sides of rivers/streams as moist tropical riparian forest, including *Terminalia arjuna*, *Hopea parviflora*, *Mangifera indica*, *Drypetes roxburghii*, *Garcinia gummi-gutta*, *Mallotus stenanthus*, *Calophyllum calaba*, *Syzygium cumini*, and *Schefflera racemosa* are common inhabitants of the extant flora in the region and are recorded in good abundance in the studied core. During MIS-2 (38–36 ka) the graminaceous cuticle increases to 38% with a fall in Foraminifera (40%) as compared to that recorded in MIS-1.

The sediment accumulation rate does not show much difference but remained static until 3c with a sharp increase of 11.3 cm/yr. Overall results show high fluctuating trend in percentage of Foraminifera and *Botryococcus* remains along with the graminaceous cuticles. The pollen spectra display herbaceous pollen grains and do not show any characteristic rain forest pollen assemblage during MIS-1 (36–0 cm; 12–0 ka). High percentage of freshwater algae *Botryococcus* throughout in the core except at some intervals shows the continuity in precipitation either through south-west monsoon or north-east monsoon. The magnitude of both these monsoon may have varied during the glacial and interglacial cycles that triggered the oceanic productivity.

Overall results reveal the similarity in the position of shoreline between MIS-5a and present day. Accordingly, the terrestrial influx from land with regard to pollen/spores should have been similar, as the South-Western Ghat flora and the riparian or estuarine plant taxa are very much in existence today. However, pollen evidences of about more than 80 taxa were recorded during MIS-5a but during Holocene the pollen record diminished drastically. It is inferred that the intensity of both south-west and north-east monsoon has decreased due to which the magnitude of terrestrial influx and the distance of its transport into the marine realm has decreased. Results reveal that during MIS-5a, the precipitation was higher than at present and the environmental conditions were more conducive for rain forest vegetation in South-Western Ghats. Palynological study from Miocene Varkala deposits of Kerala documents about 49 pollen taxa belonging to 43 families that are still distributed in the tropical Indo-West Pacific region of the present day (Ramanujam, 1987; Ramanujam et al., 1991; Campanile et al., 2008).

These sediments were deposited in marginal marine brackish lagoons as well as brackish and freshwater swamps. The reconstructed climatic parameters for the Varkala pollen flora document a seasonal precipitation pattern with a dry and a wet period and moderate rainfalls during the warmest period. This seasonality is similar to that of the recent annual precipitation cycle in southern Kerala and affirms the presence of a monsoon-like atmospheric circulation over South India since the Middle Miocene Climate Optimum (MMCO). The vegetation in the South-Western Ghats probably took refuge in the riparian zone or around large water bodies within the forests during adverse periods. Despite the wave of plant extinctions that occurred with increasing aridity from the Neogene to Quaternary, the fossil record shows that large taxonomic components of the ancient flora remain in contemporary communities of Mediterranean regions and tropical non-Mediterranean regions around the world (Valiente-Banuet et al., 2006) and include some of the most abundant modern families like Anacardiaceae, Avicenniaceae, Dipterocarpaceae, Euphorbiaceae, Meliaceae, Rhizophoraceae, Rubiaceae, Rutaceae, Sapotaceae, and Sonneratiaceae. The pollen morphological resemblance of Tertiary and Quaternary pollen has been recorded showing similar morphological features (Prasad et al., 2009). The ecological characteristics of ancient taxa appear to be highly conserved over geological time scales. Thus, the Pleistocene palynological archive from Changanacherry on land

and from the Arabian Sea in the present study shows its lineage to tropical rain forest which occurred in most parts during the Paleogene and Neogene in India and Southeast Asia. Later, the LGM period was vulnerable which triggered the local extinction, migration and replacement of the vegetation in Indian sub-continent. The hypothesis of 'plant refugia' cannot be ruled out and the existing endemic vegetation in South-Western Ghats is therefore, the legacy of Paleogene/Neogene flora and is rightly called as fossil flora.

5. Conclusion

The organic remains preserved in marine sediment as palynomorphs could be used as tracers of the origin, status of rain forest vegetation and other biogenic fluxes which permitted characterization of past depositional environments during the glacial and interglacial cycles since ~140 ka in the south-eastern Arabian Sea covering MIS-6 to MIS-1 (Marine Isotopic Stages). The provenance of the sediment in the EAS is the west coast of the Indian Peninsula evident from reworked Neogene nanoplanktons (*Discoaster* spp.) from the Varkala Formation along the coastline in Kerala. Dominance of rain forest vegetation (~36 species) and mangroves (~3 species) has been recorded during MIS-5a although 6 species of these have been observed during MIS-6. Climate induced sea level fluctuations largely affected the sedimentary dynamics and oceanic productivity. On the basis of marine versus terrestrial organic matter and earlier palynological records from land and the Arabian Sea sediment it is inferred that the highstand during MIS 5a was similar to the present day shoreline. The glacial stages post YTT were more frequent and vulnerable to the South-Western Ghat rain forest. Thus, the stages reached their climax in the Last Glacial Maximum (LGM) during which the Savanna grassland was dominant and a vast open land occurred as the sea level retreated to its maximum of -120 m from the present level. The hypothesis of 'plant refugia' cannot be ruled out as the rain forest rejuvenated with the onset of warm

and humid Holocene climate in the Western Ghats. The South-Western Ghats endemic flora (known as fossil flora) show similarity with the Paleogene–Neogene pollen assemblage comprising some of the most abundant modern families like Anacardiaceae, Avicenniaceae, Dipterocarpaceae, Euphorbiaceae, Meliaceae, Rhizophoraceae, Rubiaceae, Rutaceae, Sapotaceae, Sonneratiaceae Campanulaceae, and Asteraceae. The ecological characteristics of palynomorph assemblage seem to be highly conserved as the earlier reconstructed Miocene (Varkala Formation) pollen flora documents a seasonal precipitation pattern with a dry and a wet period and moderate rainfalls during the warmest period. It is inferred from the present study that the seasonality remained similar to that of the recent annual precipitation cycle in southern Kerala and affirms the presence of a monsoon-like atmospheric circulation over South India since the Middle Miocene Climate Optimum (MMCO). The fluctuation in the relative sea level was largely induced by glacial and interglacial climatic cycles which defined the input of terrestrial clastics in the marine realm.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.palaeo.2014.06.020>. These data include Google maps of the most important areas described in this article.

References

- Akers, W.H., 1965. Pliocene–Pleistocene boundary, northern Gulf of Mexico. *Science* 149, 741.
- Aubry, M.P., 1985. *Handbook of Cenozoic Calcareous Nanoplankton*. Micropaleontology Press, American Museum of Natural History, New York (265 pp.).
- Banakar, V.K., Oba, T., Chodankar, A.R., Kuramoto, V.K., Yamamoto, T., Minagawa, M., 2005. Monsoon related changes in sea surface productivity and water column denitrification in the Eastern Arabian Sea during the last glacial cycle. *Mar. Geol.* 219 (2–3), 99–108.
- Barboni, D., Bonnefille, R., 2001. Precipitation signal in modern pollen rain from tropical forests of Southwest India. *Rev. Palaeobot. Palynol.* 114, 239–258.
- Barboni, D., Bonnefille, R., Prasad, S., Ramesh, B.R., 2003. Variation in the modern pollen from tropical evergreen forest and the monsoon seasonality gradient in SW India. *J. Veg. Sci.* 14, 551–562.

- Barbonie, D., Bonnefille, R., Alexangre, A., Meunier, J.D., 1999. Phytoliths as paleoenvironmental indicators, West Side Middle Awash Valley, Ethiopia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 152 (1–2), 87–100.
- Beaufort, L., 1996. Dynamics of the monsoon in the Equatorial Indian Ocean over the last 260,000 years. *Quat. Int.* 31, 13–18.
- Bentaleb, I., Caratini, C., Fontugne, M., Thérèse, M., Kerfourn, M., Pascal, J.P., Tissot, C., 1997. Monsoon regime variations during the Late Holocene in the southwestern India third millennium BC climate change and old world collapse. *NATO ASI Series*, vol. 49, pp. 475–488.
- Bera, S.K., Farooqui, A., 2000. Mid-Holocene vegetation and climate of South Indian Montane. *J. Palaeontol. Soc. India* 45, 49–56.
- Bera, S.K., Farooqui, A., Gupta, H.P., 1997. Late Pleistocene/Holocene vegetation and environment in and around Marian Shola, Palni Hills, Tamil Nadu. *Palaeobotanist* 46, 191–195.
- Blasco, F., Thanikaimoni, G., 1974. Late Quaternary vegetational history of southern region. In: Surange, K.R. (Ed.), *Aspects and Appraisal of Indian Palaeobotany*. Birbal Sahni Institute of Palaeobotany, Lucknow, pp. 632–643.
- Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* 365, 143–147.
- Bonnefille, R., Anupama, K., Barboni, D., Pascal, J.P., Prasad, S., Sutra, J.P., 1999. Modern pollen spectra and vegetation from tropical South India and Sri Lanka. *J. Biogeogr* 26, 1255–1280.
- Campanile, D., Nambiar, C.G., Bishop, P., Widdowson, M., Brown, R., 2008. Sedimentation record in the Konkan–Kerala Basin: implications for the evolution of the Western Ghats and the Western Indian passive margin. *Basin Res.* 20, 3–22.
- Caratini, C., Bentaleb, I., Fontugne, M., Morzadec-Kerfourn, M.T., Pascal, J.P., Tissot, C., 1994. A less humid climate since ca. 3500 yr BP from marine cores off Karwar, western India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 109, 371–384. CGWB, 1992. Final Technical Report on SIDA Assisted Coastal Kerala Ground Water Project, pp. 1–233.
- Corlett, R.T., Primack, R.B., 2006. Tropical rainforests and the need for cross-continental comparisons. *Trends Ecol. Evol.* 21, 104–110.
- Demske, D., Tarasov, P.E., Nakagawa, T., 2012. Atlas of pollen, spores and further nonpollen palynomorphs recorded in the glacial–interglacial late Quaternary sediments of Lake Suigetsu, central Japan. *Quat. Int.* 290–291, 164–238.

- Dey, A.K., 1961. The Miocene mollusca from Quilon, Kerala (India). *Memoirs of the Geological Survey of India, Palaeontologia Indica, New Series*, 36, pp. 1–117.
- Duplessy, J.C., 1982. Glacial to Interglacial contrast in the northern Indian Ocean. *Nature* 295, 494–498.
- Edwards, L., Anderle, V.A.S., 1992. Distribution of selected dinoflagellate cysts in modern marine sediments. In: Head, M.J., Wrenn, J.H. (Eds.), *Neogene and Quaternary Dinoflagellate Cysts and Acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 259–288.
- Erdtman, G., 1943. Pollenspektra från svenska växtsamhällen jämte pollenanalytiska markstudier i södra Lappland. *GFF* 65, 37–66.
- Ericson, D.B., Ewing, M., Wollin, G., 1963. Pliocene–Pleistocene boundary in deep-sea sediments: extinctions and evolutionary changes in microfossils clearly define the abrupt onset of the Pleistocene. *Science* 139 (3556), 727–737.
- Fairbanks, R., Matthews, R.K., 1978. The marine oxygen isotope record in Pleistocene coral, Barbados, West Indies. *Quat. Res.* 10, 181–196.
- Farooqui, A., Ray, J.G., Farooqui, S.A., Tiwari, R.K., Khan, Z.A., 2010. Palyno-diversity, sea level and climate prior to 40 ka in Indian Peninsula, Kerala. *Quat. Int.* 213, 2–11.
- Fontugne, M.R., Duplessy, J.C., 1986. Variations of the monsoon regime during the upper Quaternary: evidence from carbon isotopic record of organic matter in north Indian Ocean sediment cores. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 56, 69–88.
- Frenzel, B., Pécsi, M., Velichko, A.A., 1992. *Atlas of Paleoclimates and Paleoenvironments of the Northern Hemisphere. Late Pleistocene–Holocene*, Verlag, Budapest-Stuttgart.
- Ganesh, T.Z., Ganesam, M., Devy, S., Davidar, P., Bawa, K.S., 1996. Assessment of plant biodiversity at a mid-elevation evergreen forest of Kalakad–Mundanthurai Tiger reserve, Western Ghats, India. *Curr. Sci.* 71, 379–392.
- Gardiner, J.S., 1906. *The Fauna and Geography of the Maldive and Laccadive Archipelagoes, Being the Account of the Work Carried Out and of Collections Made by an Expedition During the Years 1899 and 1900*, vol. 2. University Press, Cambridge.
- Gathorne-Hardy, F., Syaukani, J., Davies, R.G., Peggleton, P., Jones, D.T., 2002. Quaternary rainforest refugia in South-east Asia: using termites (Isoptera) as indicators. *Biol. J. Linn. Soc.* 75, 453–466.
- Ghate, U., Joshi, N.V., Gadgil, M., 1998. On the patterns of tree diversity in the western Ghats of India. *Curr. Sci.* 75, 594–603.
- Givinish, T.J., 1999. On the causes of gradients in tropical tree diversity. *J. Ecol.* 87, 193–210.

- Goodfriend, G.A., Margaritz, M., 1988. Palaeosols and late Pleistocene rainfall fluctuations in the Negev Desert. *Nature* 144–147.
- Gupta, H.P., 1973. Quaternary vegetational history of Ootacamund, Nilgiris, South India. Kakathope and Rees Corner. *Palaeobotanist* 20 (1), 74–90.
- Gupta, H.P., Bera, S.K., 1996. Silent Valley: a correlation between pollen spectra and vegetation. *Palaeobotanist* 43, 139–144.
- Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P.C., Vail, P., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: Graciansky, P.C., et al. (Eds.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Special Pub., 60, pp. 3–13 (charts 1–8).
- Harland, R., 1983. Distribution maps of recent dinoflagellate cysts in bottom sediments from the North Atlantic Ocean and adjacent seas. *Palaeontology* 26, 321–387.
- Hooghiemstra, H., 1988. Palynological records from northwest African marine sediments: a general outline of the interpretation of the pollen signal. *Philos. Trans. R. Soc. Lond. B* 318, 431–449.
- Hooghiemstra, H., Van der Hammen, T., 1998. Neogene and Quaternary development of the neotropical rain forest: the forest refugia hypothesis, and a literature overview. *Earth-Sci. Rev.* 44, 147–183.
- Hooghiemstra, H., Van der Hammen, T., 2004. Quaternary ice-age dynamics in the Colombian Andes: developing an understanding of our legacy. *Philos. Trans. R. Soc. Lond. B* 359, 173–181.
- Huntley, B., Webb, T., 1989. Migration: species' response to climatic variations caused by changes in the earth's orbit. *J. Biogeogr.* 16, 5–19.
- Ishfaq, A.M., Pattan, J.N., Matta, V.M., Banakar, V.K., 2013. Variation of Paleo-productivity and Terrigenous Input in the Eastern Arabian Sea during the past 100 ka. *J. Geol. Soc. India* 81, 647–654.
- Knox, R.A., 1987. The Indian Ocean: interaction with the monsoon. In: Fein, J.S., Stephens, P.L. (Eds.), *Monsoon*. John Wiley & Sons, pp. 365–397.
- Kumaran, K.P.N., Limaye, R.B., Nair, K.M., Padmalal, D., 2008. Palaeoecological and palaeoclimate potential of subsurface palynological data from the Late Quaternary sediments of South Kerala Sedimentary Basin, southwest India. *Curr. Sci.* 95 (4), 515–526.
- Lambert, B., 2003. Micropaleontological investigations in the modern Mahakam delta, East Kalimantan, Indonesia. *Carnets de Géologie — Notebooks on Geology, Maintenon, Article 2003/02, CG2003_A02_BL*, pp. 1–21.

- Lézine, A.M., Vergaud-Grazzini, 1994. Evidence of forest extension in west Africa since 22,000 BP: a pollen record from the eastern tropical Atlantic. *Quat. Sci. Rev.* 12, 203–210
- Lu, H., Liu, K., 2003. Phytoliths of common grasses in the coastal environments of southeastern USA. *Estuar. Coast. Shelf Sci.* 58, 587–600.
- Meher-Homji, V.M., Gupta, H.P., 1999. A critical appraisal of vegetation and climate changes during quaternary in the Indian Region. *Proc. Indian Natl. Sci. Acad.* B65, 205–244.
- Menon, K.K., 1967. The lithology and sequence of the Quilon Beds. *Proc. Indian Natl. Sci. Acad.* 65, 20–25.
- Morley, R.J., 2000. *Origin and Evolution of Tropical Rainforests*. John Wiley & Sons, West Sussex, UK (Wiley, plates 362).
- Mulholland, S.C., 1989. Phytolith shape frequencies in North Dakota grasses: a comparison to general patterns. *J. Archaeol. Sci.* 16, 489–511.
- Narayanan, A.C., Priju, C.P., Rajagopalan, G., 2002. Late Quaternary peat deposits from Vembanad Lake (lagoon), Kerala, SW coast of India. *Curr. Sci.* 83, 318–321.
- Narayanan, V., Anirudhan, S., Grottoli, A.G., 2007. Oxygen and carbon isotope analysis of the Miocene limestone of Kerala and its implications to palaeoclimate and its depositional setting. *Curr. Sci.* 93, 1155–1158.
- Nayar, T.S., 1990. *Pollen Flora of Maharashtra State India*, 157 p, 67 Plates.
- Pascal, J.P., 1982. *Bioclimatics of the Western Ghats of India*, vol. 88. Institut Francais de Pondiche' ry, Travaux de la Section Scientifique et Technique, Pondichery, India.
- Pascal, J.P., 1986. Explanatory booklet on the forest map of South India. Inst Fr Pondichery, Trav Sec Sct Tech, Series 18. Forest Department and the French Institute of Pondicherry, Karnataka.
- Pascal, J.P., 1988. *Wet Evergreen Forests of the Western Ghats of India. Ecology, Structure, Floristic Composition and Succession*. Rapport Institut français Pondichery, India.
- Pascal, J.P., 1991. Floristic composition and distribution of evergreen forests in the western Ghats, India. *Palaeobotanist* 39, 110–126.
- Pattan, J.N., Pearce, N.J.G., 2009. Bottom water oxygenation history in southeastern Arabian Sea during the past 140 ka: results from redox-sensitive elements. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 280 (3–4), 396–405.
- Pattan, J.N., Masuzawa, T., Naidu, P.D., Parthiban, G., Yamamoto, M., 2003. Productivity fluctuations in the southeastern Arabian Sea during the last 140 ka. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 193, 575–590.

- Pattan, J.N., Masuzawa, T., Yamamoto, M., 2005. Variations in terrigenous sediment discharge in a sediment core from southeastern Arabian Sea during the last 140 ka. *Curr. Sci.* 89, 1421–1425.
- Piller, W.E., Reuter, M., Harzhauser, M., Kroh, A., Rögl, F., Coric, S., 2010. The Quilon Limestone (Kerala Basin/India) — an archive for Miocene Indo-Pacific sea grass beds. *Geophysical Research Abstracts*, vol. 12. EGU General Assembly (EGU2010-6751, 2010).
- Plana, V., Gascoigne, A., Forest, L.L., Harris, D., Pennington, R.T., 2004. Pleistocene and pre-Pleistocene *Begonia* speciation in Africa. *Mol. Phylogenetic Evol.* 31, 449–461.
- Prabhu, C.N., Shankar, R., Anupma, K., Taieb, M., Bonnefille, R., Vidal, L., Prasad, S., 2004. A 200-ka pollen and oxygen isotope record from two sediment cores from the eastern Arabian Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 214, 309–321.
- Prain, D., 1894. Botany of the Laccadives, being natural history notes from H.M.1.M. Survey Steamer “Investigator”. *J. Bombay Nat. Hist. Soc.* 7, 268–295 (1892; 8: 57–86, 1893; 488).
- Prasad, V., Farooqui, A., Tripathi, S.K.M., Garg, R., Thakur, B., 2009. Evidence of Late Palaeocene–Early Eocene equatorial rain forest Refugia in southern western Ghats, India. *J. Biosci.* 34 (5), 777–797.
- Prasanna Kumar, S., Ramaiah, N., Gauns, M., Sarma, V.V.S.S., Muraleedharan, P.M., Raghukumar, S., Dileep Kumar, M., Madhupratap, M., 2001. Physical forcing of biological productivity in the Northern Arabian Sea during the Northeast Monsoon. *Deep-Sea Res. II Top. Stud. Oceanogr.* 48 (6–7), 1115–1126.
- Prell, W.L., Hutson, W.H., Williams, D.F., Be, A.W.H., Geitzenauer, H., Molfino, B., 1980. Surface circulation of the Indian Ocean during the Last Glacial Maximum, approximately 18,000 yr. B.P. *Quat. Res.* 14, 309–336.
- Qasim, S.Z., 1982. Oceanography of the Northern Arabian Sea. *Deep-Sea Res.* 29, 1041–1068.
- Rajagopalan, B., Lall, U., Cane, M.A., 1997. Anomalous ENSO occurrences: an alternate view. *J. Clim.* 10 (9), 2351–2357.
- Ramanujam, C.G.K., 1987. Palynology of the Neogene Warkalli Beds of Kerala State in South India. *J. Palaeontol. Soc. India* 32, 26–46.
- Ramanujam, C.G.K., Rao, G.M., Reddy, P.R., 1991. Palynological studies of subsurface sediments at Mynagapalli, Quilon District, Kerala State. *Biovigyanam* 17 (1), 1–11.
- Ramesh, B.R., Pascal, J.P., 1997. Atlas of Endemics of the Western Ghats (India). *Institute Francais de Pondichery, Pondichery*.

- Reuter, M., Piller, W.E., Harzhauser, M., Kroh, A., Rogl, F., Coric, S., 2010. Quilon limestone, Kerala Basin, India: an archive for Miocene Indo-Pacific sea grass beds. *Lethaia* 44, 76–86.
- Reuter, M., Kern, A.K., Harzhauser, M., Kroh, A., Piller, W.E., 2012. Global warming and South Indian monsoon rainfall—lessons from the Mid-Miocene. *Gondwana Res.* 23, 1172–1177.
- Runge, J., 1997. Altersstellung und paläoklimatische Interpretation von Decksedimenten, Steinlagen (stone-lines) und Verwitterungsbildungen in Ostzair (Zentralafrika). *Geoökodynamik* 18 2/3, 91–108 (Bensheim, Germany).
- Sarkar, A., Ramesh, R., Bhattacharya, S.K., Rajagopalan, G., 1990. Oxygen isotope evidence for a stronger winter monsoon current during the last glaciation. *Nature* 343, 549–551.
- Schulz, H., von Rad, U., Erlenkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature* 393, 54–57.
- Shackleton, N., Hall, M.A., Vincent, E., 2000. Phase relationships between millennial-scale events 64,000–24,000 years ago. *Paleoceanography* 15 (6), 565–569.
- Shankar, U., Thakur, N.K., Reddy, S.I., 2004. Estimation of geothermal gradients and heat flow from bottom simulating reflector along the Kerala–Konkan basin of Western Continental Margin of India. *Curr. Sci.* 87, 250–253.
- Sukumar, R., Ramesh, R., Pant, R.K., Rajagopalan, G., 1993. A $\delta^{13}\text{C}$ record of late Quaternary climate change from tropical peats in southern India. *Nature* 364, 703–706.
- Tissot, C., Chikhi, H., Nayar, T.S., 1994. Pollen of Wet Evergreen Forests of the Western Ghats, India. Institut français, Pondicherry, India.
- Toscano, M.A., Lundberg, J., 1999. Submerged late Pleistocene reefs on the tectonically stable S.E. Florida margin: high-precision geochronology, stratigraphy, resolution of substage 5a sea-level elevation, and orbital forcing. *Quat. Sci. Rev.* 18, 753–767.
- Twiss, P.C., Suess, E., Smith, R.M., 1969. Morphological classification of grass phytoliths. *Soil Sci. Soc. Am. Proc.* 33, 105–115.
- Vaidyanadhan, R., Ramakrishnan, M., 2008. Geology of India. Geological Society of India, Bangalore (994 pp.).
- Valiente-Banuet, A., Vital, A., Verdu, M., Callaway, R.M., 2006. Modern Quaternary plant lineages promote diversity through facilitation of ancient Tertiary lineages. *Proc. Natl. Acad. Sci. U. S. A.* 103, 16812–16817.
- van Andel, T.H., Tzedakis, P.C., 1996. Palaeolithic landscapes of Europe and environs 150,000–25,000 years ago: an overview. *Quat. Sci. Rev.* 15, 481–500.

- Van Campo, E., 1986. Monsoon fluctuations in two 20,000-Yr B.P. — oxygen-isotope pollen records off southwest India. *Quat. Res.* 26, 376–388.
- Van Campo, E., Duplessy, J.C., Rossignol-Strick, M., 1982. Climatic conditions deduced from a 150 kyr oxygen isotope-pollen record from the Arabian Sea. *Nature* 296 (1982), 56–59.
- Vasanthy, G., 1988. Pollen analysis of late Quaternary sediments: evolution of upland savanna in Sandynallah (Nilgiris, South India). *Rev. Palaeobot. Palynol.* 55, 175–192.
- Vishnu-Mittre, Gupta, H.P., 1971. Origin of Shola forest in the Nilgiris, South India. *Palaeobotanist* 19 (1), 110–114.
- Wall, D., Dale, B., Lohmann, G., Smith, W., 1977. The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the North and South Atlantic Oceans and adjacent seas. *Mar. Micropaleontol.* 2, 121–200.
- Wray, J.L., Ellis, C.H., 1965. Discoaster extinction in neritic sediments, northern Gulf of Mexico. *Am. Assoc. Petrol. Geol. Bull.* 49 (1), 98–99.
- Wright, J.D., 2000. Global climate change in marine stable isotope records. In: Noller, Jay S., Sowers, Janet M., Lettis, William R. (Eds.), *Quaternary Geochronology: Methods and Applications*, 2000. American Geophysical Union, 4, pp. 1–582.

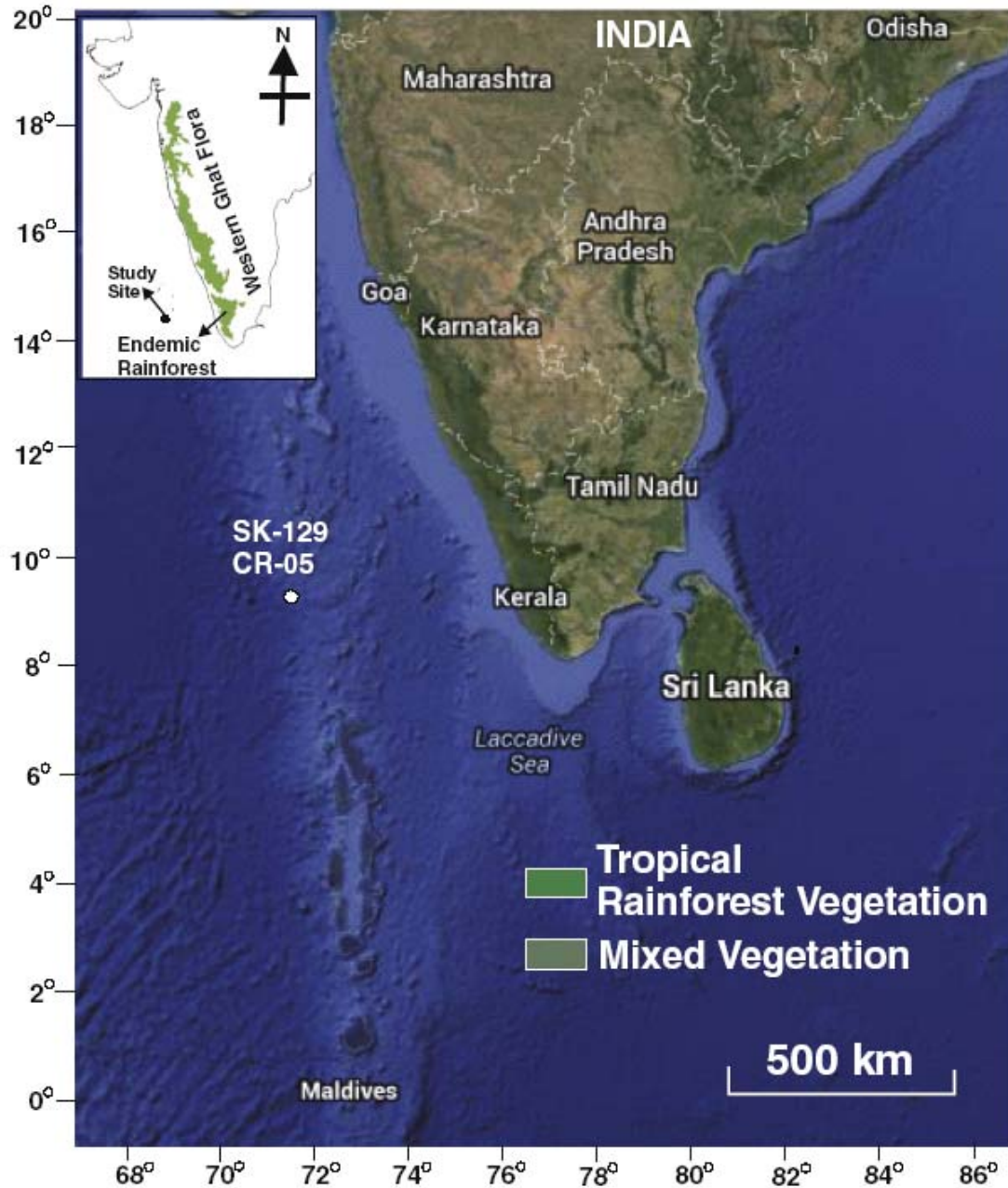


Fig. 1. Satellite map showing the position of core SK129/CR-05 and the vegetational cover in the Indian Peninsula and adjoining areas.

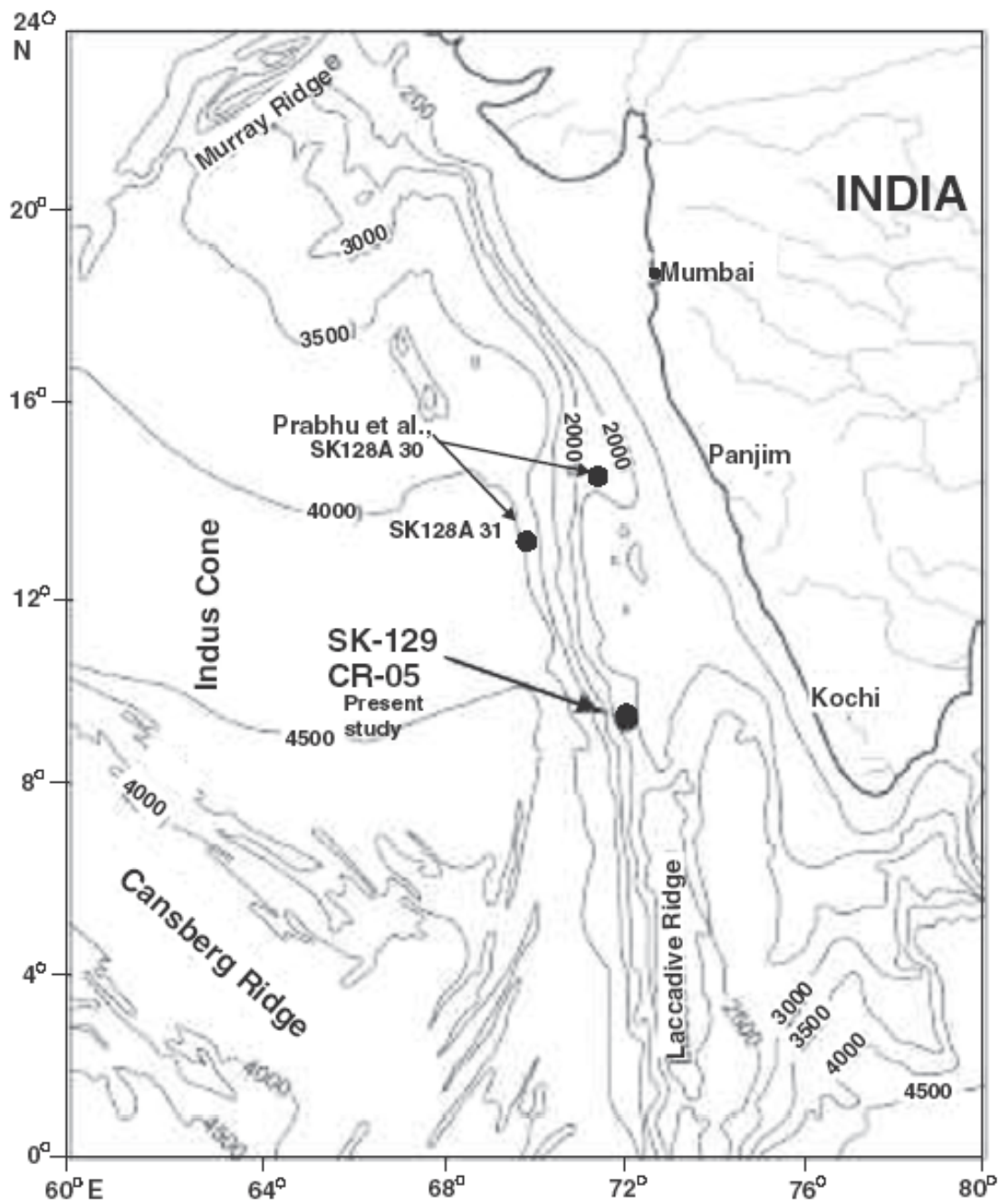


Fig. 2. The position of the studied core in the south-eastern Arabian Sea and its proximity to the west coast of India.

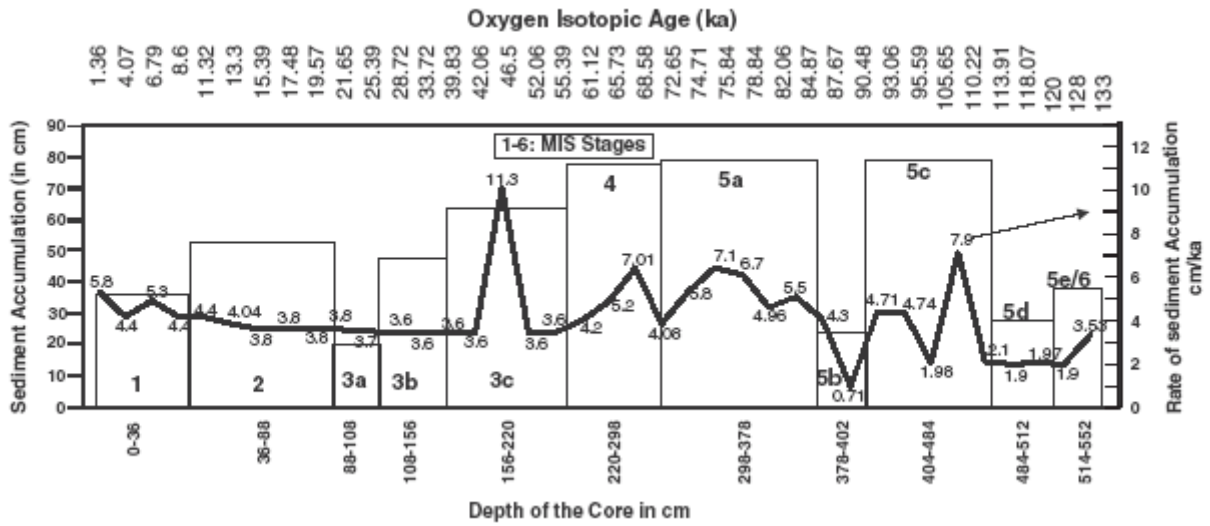


Fig. 3. The magnitude and rate of sediment accumulation corresponding to Marine Isotopic stages.

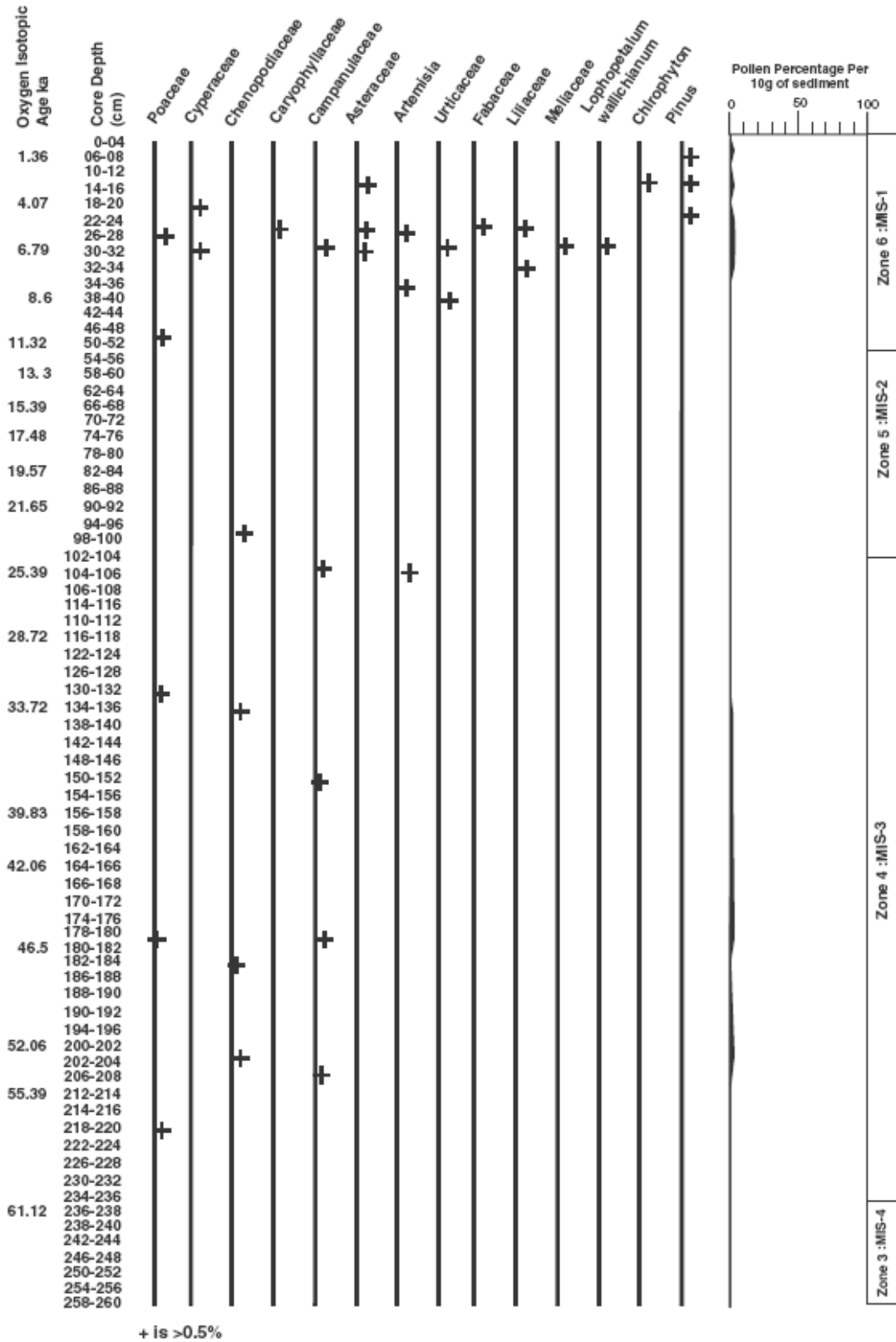


Fig. 4. Occurrence of the pollen from present to 64 ka in SK-129/CR-05 core, south-eastern Arabian Sea.

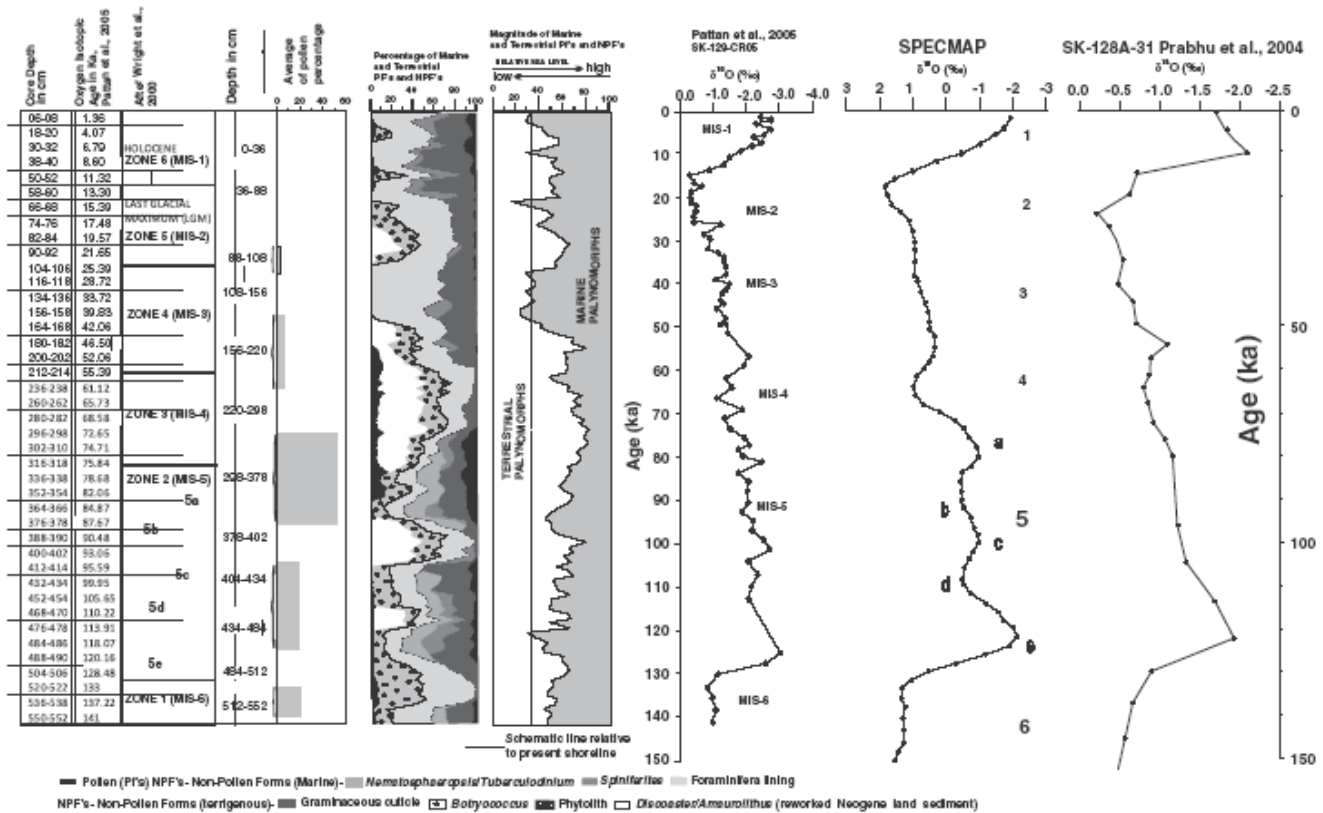


Fig. 6. Total assemblage of palynomorphs (pollen and non-pollen forms), comparative oxygen isotopic age record and schematic graphs representing sea level rise and fall in chronological order since ~140 ka on the basis of marine versus terrestrial palynomorphs in the south-eastern Arabian Sea.

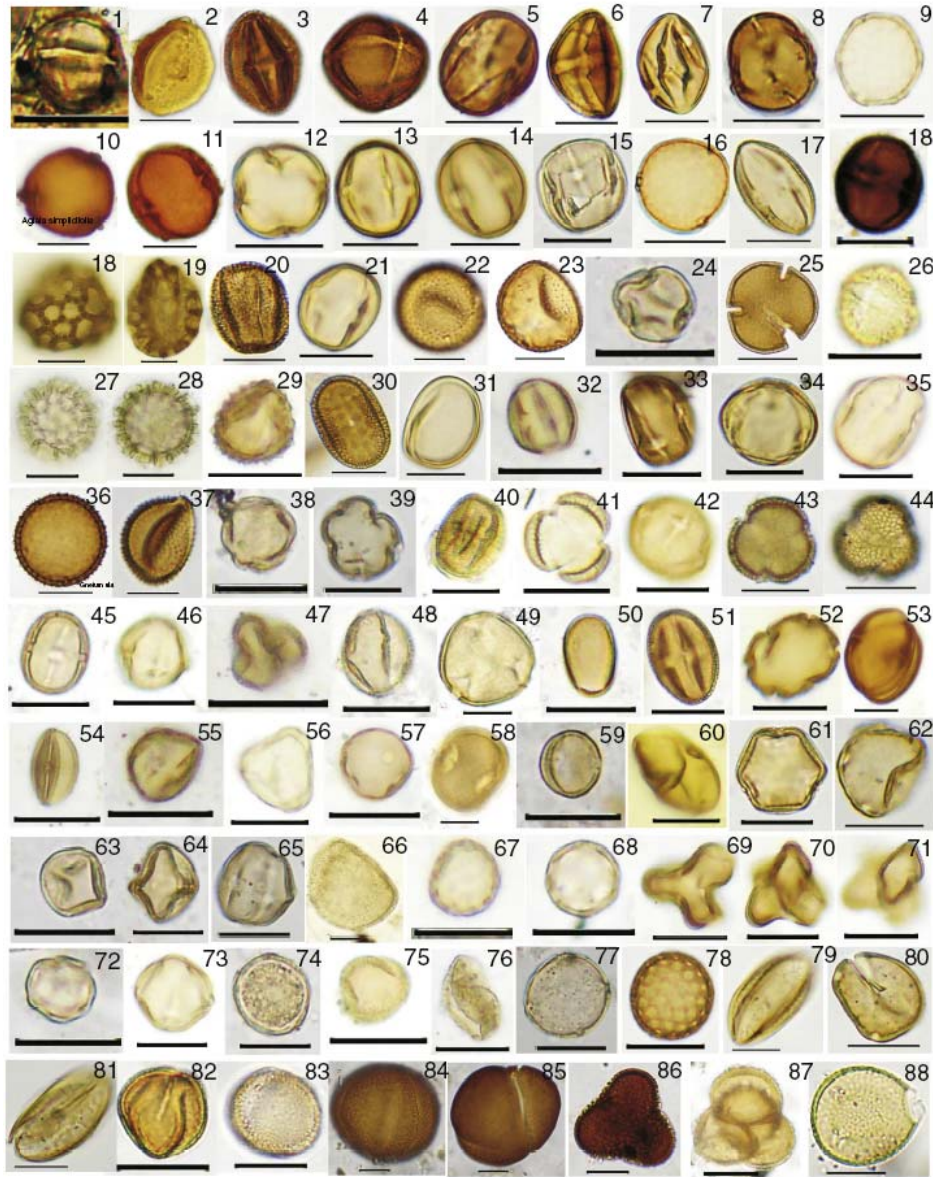


Fig. 7. Light microscopic photomicrographs (all scale= 10 μ m).1. Rhizophora; 2. Sonneratia; 3. Excoecaria; 4. Mallotus beddomei; 5. Walsura; 6. Humboldtia; 7. Palaquium; 8. Nothopegia travancorica; 9. Hopea; 10. Aglaia simplicifolia; 11. Luvunga (Rutaceae); 12–13. Dysoxylum malabaricum; 14. Dysoxylumbuxifolia; 15. Meliaceae; 16. Moraceae; 17. Semecarpus; 18. Murraya paniculata; 19. Psychotria annamalayana; 20. Psychotria flavida; 21. Violaceae; 22. Sauropus androgynus; 23–24. Unidentified; 25. Tiliaceae; 26. Solanaceae; 27–28. Myristicamalabarica; 29. Asteraceae; 30. Justicia; 31. Liliaceae; 32. Rosaceae, Prunus type; 33–34. Meliaceae; 35. Rutaceae; 36. Gnetum; 37. Clerodendrum; 38. Terminalia; 39. Rutaceae, Limonia type; 40. Reinwardtiidendron; 41. Artemisia; 42. Garuga pinnata; 43–44. Taraktogenos macrocarpa; 45. Chrysophyllum; 46, 47. Unidentified; 48. Scolopia; 49. Goodeniaceae; 50. Liliaceae; 51. Kingiodendron; 52. Gardenia type; 53. Unidentified; 54–55. Eurya; 56. Myrtaceae; 57. Unidentified; 58. Morinda; 59. Phyllanthus; 60. Unidentified; 61. Otenophelium (Sapindaceae); 62. Campanulaceae; 63. Elaeocarpus; 64. Prunus; 65. Litsea; 66. Monstera type (Araceae); 67. Chenopodiaceae; 68. Caryophyllaceae; 69–71. Ongokea gore; 72. Portulacaceae; 73. Calophyllum; 74. Moraceae; 75. Oleaceae; 76. Arenga; 77. Plantago; 78. Chenopodiaceae; 79. Apiaceae; 80. Urticaceae; 81. Acanthaceae; 82. Shorea/Hopea; 83. Dipterocarpus spp.; 84–85. Dipterocarpus spp.; 86. Bombax; 87. Lophopetalum wightianum; 88. Erythrina

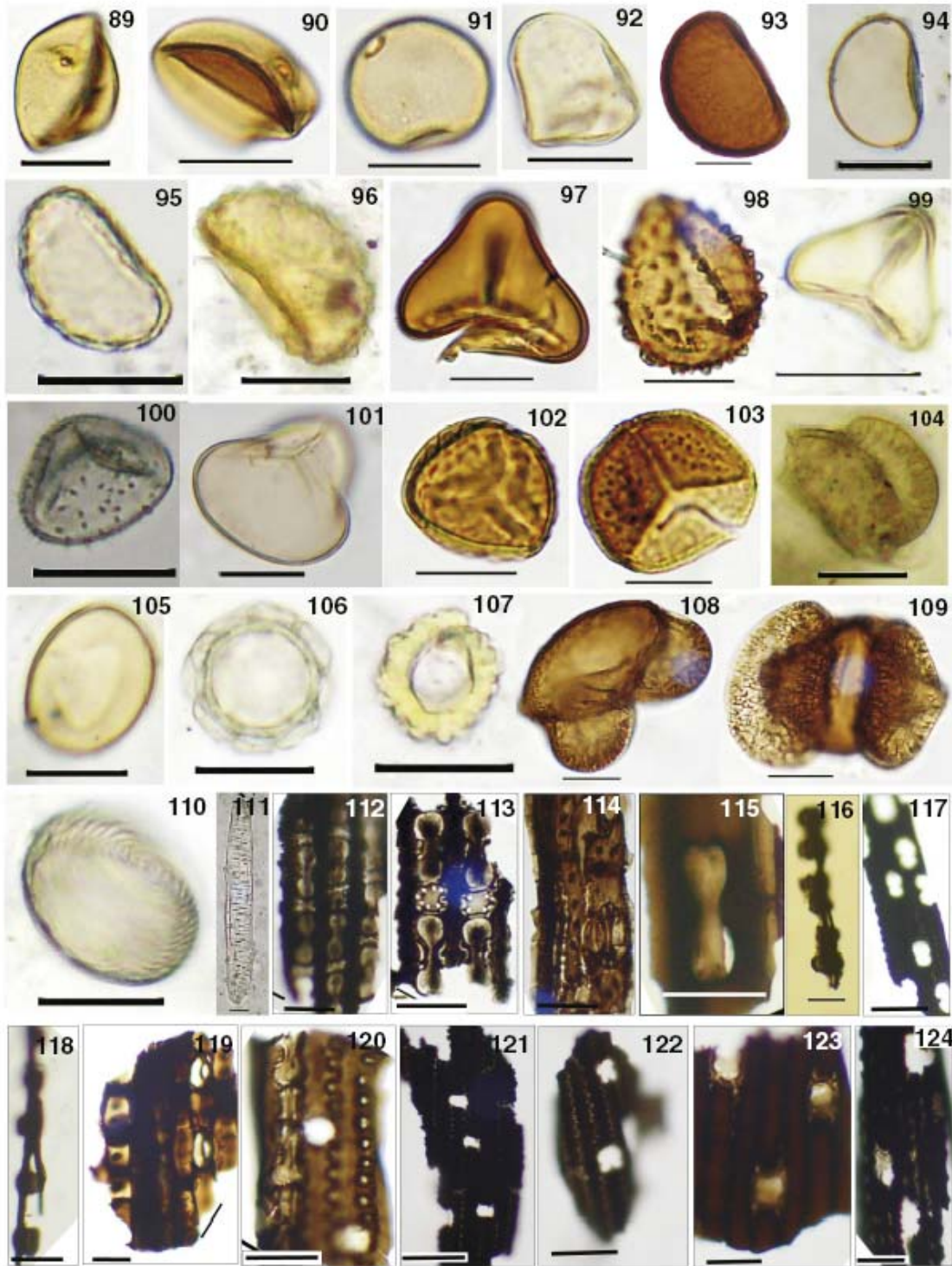


Fig. 8. 89–91. Poaceae; 92. Cyperaceae; 93–94. Psilate monolete spores; 95. Monoletes; 97–103. Trilete spores; 104. Podocarpus; 105–107. Unidentified spores; 108–109. Pinus; 110. Pseudoschizae; 111. Unidentified phytolith; 112–117. Poaceous leaf cuticles showing stomata and bilobed/dumbbell shaped phytoliths common in C4 plants. 118–124. poaceous leaf cuticles showing short celled, saddle, rondel, elliptical, crossed phytoliths common in C3 plants.

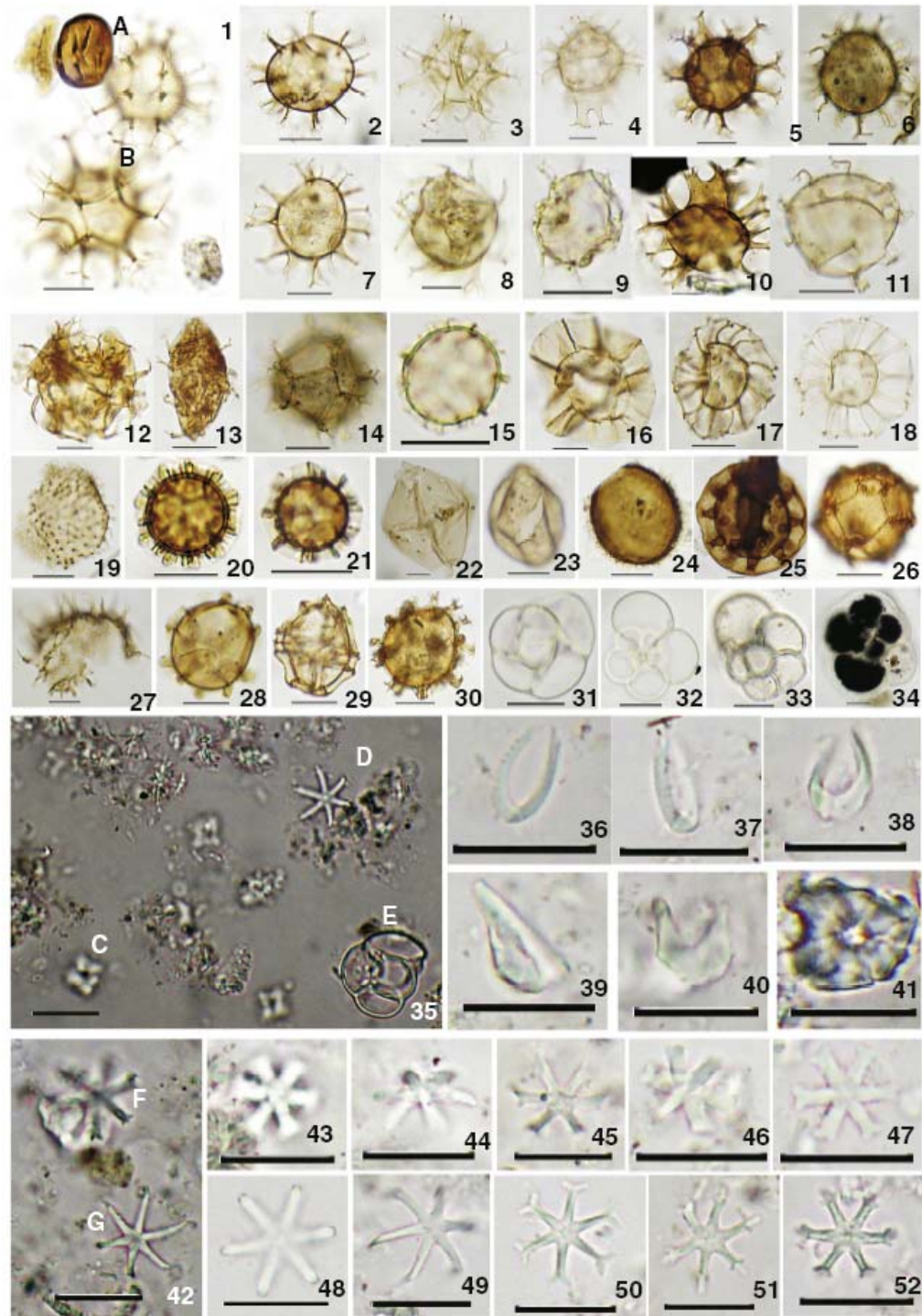


Fig. 9. 1. A—Nothopegia pollen, B—Spiniferites; 2–14. Different species of Spiniferites (Dinoflagellate cysts) in palynological slides. 15. Operculodiniumcentrocarpum; 16. Unknown; 17–18. Nemosphaeropsis labyrinthica; 19. Polykrikos; 20–23. Dinoflagellate cysts; 24. Bitectodinium; 25. Tuberculodinium vancampoae; 26. Dinoflagellate cyst; 27. Selenopemphix; 28. Tuberculodinium spp.; 29. Impagidinium; 30. Spiniferites; 31–34. Dominant forms of Foraminifera linings; 35. C. Discoaster diastypus; D. Discoaster brouweri; E. Foraminifera organic lining; 36–38. Ceratolithus cristatus; 39. Amaurolithus rugosus; 40. Amaurolithus amplificus; 41. Umbilicosphaera; 42. F — Discoaster surculus, G — D. brouweri; 43–47. Discoaster species; 48–49. D. brouweri; 50. Discoaster challengeri; 51. Discoaster bollii; 52. D. surculus.

Table 1

The depth and Lithology of the sediment core SK-129/CR-05.

Depth (cm)	Lithology
0-20	Clayey silt with rootlet
20-40	Clayey silt
40-95	Silty clay
95-160	Loosely packed black organic clay with little silt
160-180	Silt with little clay
180-230	Loosely packed black organic clay
230-300	Silt with little clay
300-352	Silt with little clay