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Palynology of Cenozoic successions of Kerala Basin: a review from the perspective of biostratigraphy and palaeoclimatic studies

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ABSTRACT

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The Kerala Basin is only onshore opportunity to study Cenozoic palaeoclimate and palaeoenvironment of southwest India encompassing Neogene global events such as Mid Miocene Climate Optimum (MMCO) and even older times of Palaeogene. The global warming during ~17–15 Ma (MMCO), enhanced annual surface temperature 3–4° C higher than the present, is equivalent to the warming predicted for the next century. Since the palaeogeographical and other general conditions have not been much changed from the Miocene Period, Neogene palaeoclimate of Kerala Basin can be considered as a possible analogue for future climate.

Many workers have studied the Cenozoic sedimentary successions of surface and subsurface for stratigraphic classification of the rocks, but still, discrepancy persists in the chronostratigraphic relationship in sedimentary successions. The palynological investigations have also been limited mainly to palynofloral and palaeoecological inferences except a few in which palynostratigraphy, correlation and age have been attempted on the basis of spore–pollen only. Major three Cenozones namely, *Triangulorites bellus* and *Crassoretitriletes vanraadshooveni* (Eocene–Oligocene) and *Malvacearumpollis bakonyensis* (Miocene) have been established. The palynological studies done in the region broadly suggest warm and humid climate with heavy rainfall. However, the recent quantitative studies have highlighted the complexity of palaeoclimatic evolution in the tropics in terms of monsoon. A time–constrained quantitative palaeovegetation and palaeoclimate reconstructions on the basis of palynology is required for evaluation of response and changes in the tropical flora of northwestern India across the major climate events. For that, the biostratigraphy of finer resolution based on systematic and integrated multi–biotic proxy is needed to establish an age model for these sedimentary successions.

Key–words—Cenozoic, Biostratigraphy, Palaeoclimate, Palynology, Kerala Basin.

केरल द्रोणी के नूतनजीव अनुक्रमों का परागाणुविज्ञान : जैवस्तरक्रमविज्ञान एवं पुराजलवायु अध्ययनों के दृष्टिकोण से समीक्षा

पूनम वर्मा एवं आभा सिंह

सारांश

मध्य मध्यनूतन जलवायु अनुकूलतम (एम एम सी ओ) तथा यहाँ तक कि पैलियोजीन के पुराने समय जैसी नियोजीन भू–मंडलीय घटनाओं को समाहित करते हुए दक्षिण पश्चिम भारत की केरल द्रोणी ही नूतनजीव पुराजलवायु एवं पुरापर्यावरण अध्ययन करने के लिए अभितट सुयोग है। ~17–15 हजार वर्ष (एम एम सी ओ) के दरम्यान भू–मंडलीय तपन, वर्तमान से उच्चतर वृद्धित वार्षिक पृष्ठीय तापमान 3–4°C, अगली शताब्दी हेतु अनुमानित तपन के बराबर है। क्योंकि मध्यनूतन काल से पुराभौगोलिक एवं अन्य सामान्य स्थितियां ज़्यादा नहीं बदली हैं, केरल द्रोणी की नियोजीन पुराजलवायु को भावी जलवायु के लिए संभाव्य सादृश्य के रूप में माना जा सकता है।

चट्टानों के स्तरिक वर्गीकरण हेतु पृष्ठीय और उपपृष्ठीय के नूतनजीव अवसादी अनुक्रमों का तमाम शोधकर्ताओं ने अध्ययन किया है, परंतु अवसादी अनुक्रमों में अभी–भी काल–स्तरिक संबंधता में विसंगति क़ायम है। कुछेक को छोड़कर, जिनमें केवल पराग बीजाणु के आधार

पर परागाणुपुष्पी एवं पुरापारिस्थितिकीय तर्कों के परागाणविक अन्वेषण सीमित ही रहें हैं। तीन प्रमुख नूतनमंडलों नामतः *त्रिअंगुलोराइटिस बेल्लस* एवं *क्रसोरेटिट्रिलेटीज वेनराडशूवेणि* (आदिनूतन–अल्पनूतन) तथा *मालवेसरमपॉल्लिस बकोनीएन्सिस* (मध्यनूमन) प्रमाणित किए गए हैं। अंचल में किए गए परागाणविक अध्ययन प्रचुर वर्षा सहित बड़े प्रताप से कोष्ण एवं आर्द्र जलवायु जताते हैं। तथापि, मानसून के संदर्भ में कटबंधों में, पुराजलवायवी उद्भव की जटिलता पर हाल ही के मात्रात्मक अध्ययनों में प्रकाश डाला गया है। परागाणुविज्ञान के आधार पर प्रमुख जलवायु घटनाओं में उत्तर पश्चिमी भारत की उष्णकटिबंधीय वनस्पति–जात में अनुक्रिया व परिवर्तनों के मूल्यांकन हेतु समय–बाधित मात्रात्मक पुरावनस्पति एवं पुराजलवायु पुनर्संरचनाओं की ज़रूरत है। इसके लिए इन अवसादी अनुक्रमों हेतु काल मॉडल सुस्थापित करने को क्रमबद्ध एवं समेकित–जीवीय प्रतिपत्री पर आधारित उत्कृष्ट–समाधान के जैवस्तरक्रमविज्ञान की आवश्यकता है।

सूचक शब्द—नूतनजीव, जैवस्तरिकी, पुराजलवायु, परागाणुविज्ञान, केरल द्रोणी।

INTRODUCTION

THE global climatic changes from greenhouse to icehouse state coupled with the collision of the Indian Plate with Asia around 55 Ma (Early Eocene). Subsequently, a sharp drop in temperature around 34 Ma (Eocene–Oligocene boundary) triggered the transformation of the extreme tropical climate of Paleogene to subtropical climate of Oligo–Miocene on the Indian subcontinent. The uplift of the Himalayan–Tibetan Plateau due to continuing convergence of India–Asia, acted a major driver for the onset of Asian monsoon during Neogene Period. The changes in geodynamics and climate resulted retraction of Paleogene tropical megathermal rainforest and, evolution and expansion of Neogene subtropical deciduous vegetation types in different parts of Indian subcontinent. The Neogene vegetation types adapted to variable seasonal rainfall condition that is characteristic of monsoonal climate. Interestingly, the monsoon history of this period is mainly reconstructed from marine sequences of the Indus Fan, Bengal Fan and the South China Sea that provide long–term variation in East Asian monsoon from catchment areas of major river basins of China and India (Clift *et al.*, 2008; Wan *et al.*, 2010). Whereas, information on monsoonal initiation, evolution, and variability through proxy records from the terrestrial region during and before Neogene is very scanty (Quade *et al.*, 1989; Sanyal *et al.*, 2004, 2005a, b, 2010; Srivastava *et al.*, 2012; Kern *et al.*, 2013; Reuter *et al.*, 2013; Khan *et al.*, 2014; Shukla *et al.*, 2014).

Being an integral part of the global climate system, the Asian monsoonal variability, precipitation in particular, greatly influence socioeconomic conditions of the human inhabitations throughout the world (An, 2000; Lovett, 2010; Cook *et al.*, 2010). In this regard, the question of universal concern arises: how the monsoon system will react to the modern scenario of global warming, will it be weaken or strengthen in future and how the biota will respond to it (An, 2000; Delsole & Shukla, 2002; Ashfaq *et al.*, 2009; You *et al.*, 2009; Cook *et al.*, 2010; You, 2010)? The proxy data compiled by You *et al.* (2009) and You (2010) indicated that during Mid–Miocene the mean global surface temperature was 3–4 °C higher than the present. The situation is equivalent to the warming of 4°C by the end of 21st Century predicted by the IPCC Fourth Report (2007). Hence, it becomes crucial to understand the forcing and development of Mid Miocene Climate Optimum (MMCO) climate change and its consequential effect and response of biota. Because, the global conditions such as high CO_2 level in atmosphere, ice–free northern hemisphere, high sea–level rise during MMCO may be analogue to the future climate trend.

Tertiary sediments of Kerala Basin (Fig. 1) preserve only such onshore opportunity of southwest India to study palaeoclimate and palaeoenvironment during Neogene global events, such as MMCO (Reuter *et al.*, 2011, 2013; Kern *et al.*, 2013) and even older times of Eocene–Oligocene (Raha *et al.*, 1987; Rao, 1990, 1995). Various palynological records are known from the onshore Tertiary sedimentary deposits of Kerala Basin, iterated age of Early Eocene through Oligocene to Miocene (Raghava Rao, 1976; Raha *et al.*, 1983, 1986, 1987; Rajendran *et al.*, 1989; Rao, 1990, 1995, 1996; Rao & Rajendran, 1996; Rao & Nair, 1998) and mainly aimed to bring out palynoflora compositions and palynostratigraphy. In the present paper, published palynological studies from Kerala Basin have been reviewed to draw an overview of the palaeovegetational history and environment of deposition. Also, a synthesis has also been done in the perspective of future palaeobiotic and palaeoclimate studies in Kerala Basin.

GEOLOGY OF THE AREA

Kerala Basin is the southern sub–basin of the pericratonic Konkan–Kerala Basin of western Indian passive continental margin. It represents sag basin development on the stretched pre–Deccan continental basement during the rifting of India from Madagascar (Singh & Lal, 1993) and provides a sedimentary record since ca. 80–90 Ma within coast parallel N–S trending grabens. Kerala Basin is separated from Konkan Basin in the north by Tellicherry Arch basement high, whereas in east bordered by steep escarpments of up to 2695 m high Western Ghats. To the west, the basin continues into offshore Kerala–Konkan Basin deep waters to the Chargos–Laccadive Ridges (Campanile *et al.*, 2008). It is the only onshore Cenozoic sedimentary basin of southwestern India, exhibit exposures of Neogene succession along the coast whereas in subsurface the older sequence exceeds 600 m depth in the central part of basin (Bose & Kartha, 1977). These sequences are mainly consists of siliciclastic sediments and interbedded clays and lignite seams. The upliftment and denudation of Western Ghats was the probable source

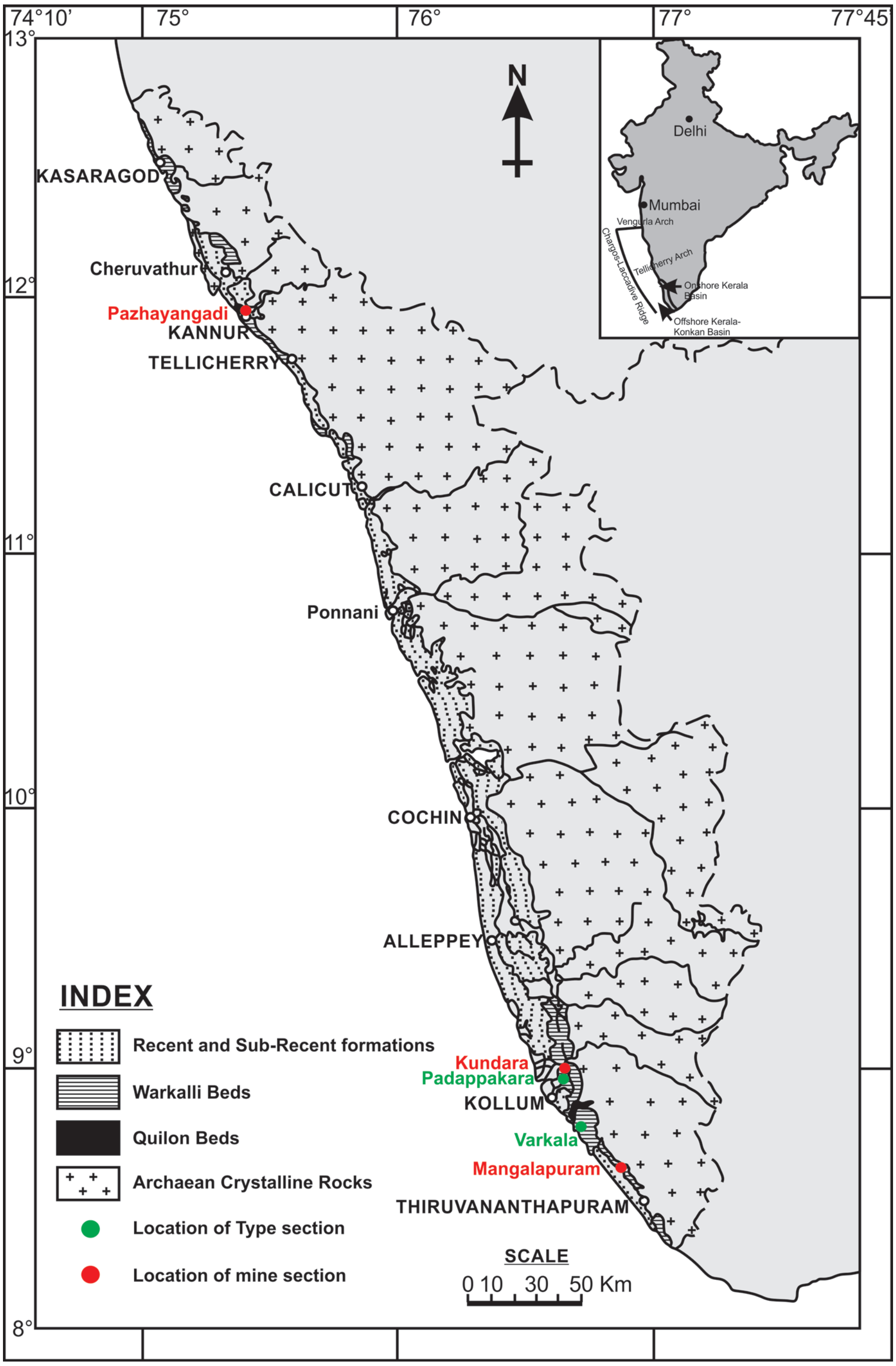


Fig. 1—Map of Kerala Basin showing localities of Tertiary exposures (after Rao, 1995).

of siliciclast (Campanile *et al.*, 2008) in the basin. Poulose & Narayanaswamy (1968) recognized two major basins of deposition: (i) between Trivandrum and Ponnani in the south and central Kerala with the maximum width of 16 km between Quilon and Kundara, and (ii) between Kannur and Kasaragod in north Kerala with the maximum width of 10 km at Cheruvattur and suggested the stratigraphic succession (Table 1).

Firstly, King (1882) and Foote (1883) divided the Cenozoic rocks of the Quilon–Varkala area into Quilon beds–consisting of limestone and calcareous clays, and Warkalli beds comprising sandstone and clay with lignites. However, exploratory borehole data of Central Ground Water Board suggests three units: (i) The Warkalli Formation (maximum thickness ~80 m) consists of variegated clays, carbonaceous clays, sands and seams of peaty lignite and (ii) the Quilon

Formation (maximum thickness ~70 m), characterized by fossiliferous limestone and intercalations of calcareous clays (Poulose & Narayanaswamy, 1968) and (iii) underlying Vaikom Formation (maximum thickness ~100 m) consists of gravel, coarse sand and carbonaceous clays with thin seams of lignite (Raghava Rao, 1976) resting unconformably over the Archaean crystalline complex. According to latest lithostratigraphic classification based on the exposed and subcrop lithofacies and their interrelationships, the entire Cenozoic succession of Kerala has been designated as The Malabar Supergroup including Quaternary Vembanad Formation and The Tertiary Warkalli Group, separated by unconformity marked by laterite horizon (Raha *et al.*, 1983). The Warkalli Group consists of Ambalapuzha, Quilon and Mayyanad formations from top to bottom in the subsurface (Table 1). The sedimentary structures together with the textural characteristics of Cherunniyoor Quarry succession indicate fluvial (meandering river) origin for the sandstone of Warkalli Group (Padmalal, 1996). Geochemical studies of Cenozoic succession at Pozhikkara Cliff suggest the prevalence of a reducing condition during deposition of carbonaceous clays (Seralathan & Padmalal, 1991). Further, based on microfossils including palynological studies many workers also reported full succession of Early Eocene through Oligocene to Miocene is preserved in the subsurface of central part of basin (Raha *et al.*, 1983, 1986; Raha & Rajendran, 1984; Rajendran *et al.*, 1987; Rao, 1990, 1995; Rao & Rajendran, 1996; Rao & Nair, 1998). However, the complexities of precise age attribution to these formations still persist (Soman, 2013).

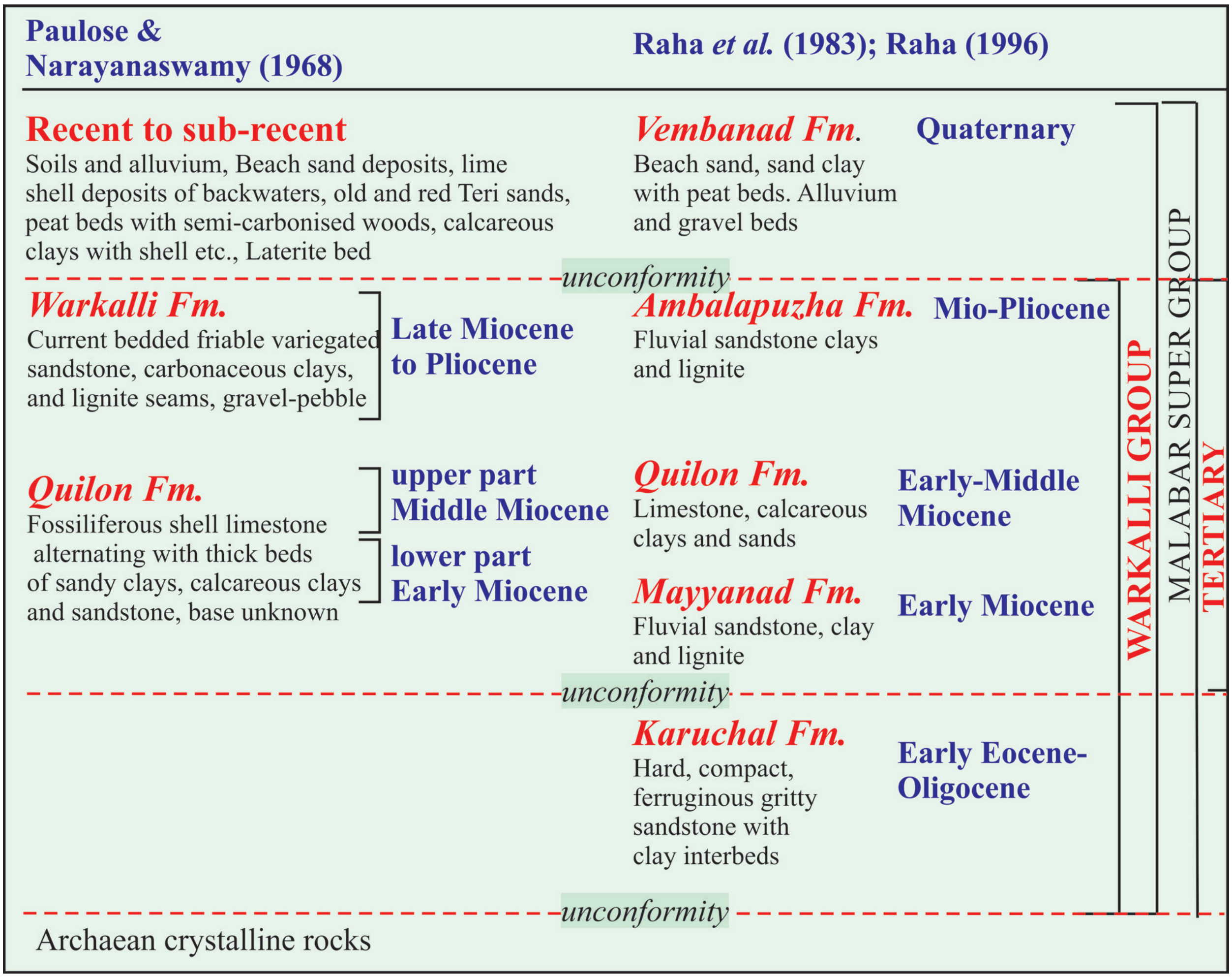
OVERVIEW OF PALYNOLOGY AND ENVIRONMENT OF DEPOSITION

Since 50's, the palynological studies of the Tertiary sediments of Kerala Basin are being conducted by several workers such as Rao and Vimal (1953), Potonie and Sah (1960), Ramanujam (1977, 1987), Rao and Ramanujam (1975, 1978, 1982), Kar and Jain (1981), Raha *et al.* (1987), Rajendran *et al.* (1989), Rao (1990, 1995, 1996), Rao and Rajendran (1996) and Rao and Nair (1998). These studies have provided floristically diverse and stratigraphically important palynological assemblages consist of more than 135 genera and 175 species of fungal remains, pteridophytic spores and angiospermous pollen from Quilon and Warkalli successions. Dinoflagellate cysts are also recorded commonly but not utilized for biostratigraphy and age correlation. On the basis of the morphological similarities, botanical affinities of Quilon and Warkalli palynofossils have been tagged with modern comparable taxa and families (Ramanujam, 1987; Singh & Rao, 1990; Rao & Nair, 1998; Rao, 2001; Reuter *et al.*, 2013; Kern *et al.*, 2013). In Table 2, 11 Pteridophytic and 50 angiospermous (6 moncotyledon and 44 dicotyledon) families with their known modern comparable taxa recorded from Quilon and Warkalli formations have been enlisted. A few common taxa in both the formations are *Anacolosidites, Araliaceaepollenites, Arecipites, Biretisporites, Bombacacidites, Chenopodipollis, Clavainaperturites, Clavaperiporites, Clavasyncolpites, Crassoretitriletes, Compositoipollenites, Crototricolpites, Dicolpopollis, Dipterocarpuspollenites, Disulcites, Favitricolporites, Florscheutzia, Foveosporites, Foveotriletes, Gleicheniidites, Gothanipollis, Grimsadalea, Halarogacidites, Hippocrateaceaedites, Iridacidites, Lacrimapollis, Lygodiumspories, Lakiapollis, Liliacidites, Longapertites, Loranthipites, Maculoporites, Malvacearumpollis, Meliapollis, Myricipites, Myricaceaepollenites, Neyvelipollenites, Ornatetradites, Osmundacidites, Pachydermites, Plumbaginaceaepites, Polygalacidites, Polypodiaceaesporites, Polypodiisporites, Polyporina, Retimonosulcites, Retipollenites, Retistephanocolpites, Rhoipites, Sapotaceoipollenites, Schizaeoisporites, Spinainaperturites, Sonnaratiopollis, Surmaspora, Symplocoipollenites, Todisporites, Thomsonipollis, Trilatiporites, Triporopollenites, Quilonipollenites, Verrucosisporites, Verrutricolporites, Warkallipollenites* and *Zonocostites*.

The palynostratigraphic zonation was attempted by Rao (1990) in Arthungal borehole, Alleppey District, Kerala. The borehole has been divided into three cenozones namely the *Triangulorites bellus* Cenozone, the *Crassoretitriletes vanraadshooveni* Cenozone, and the *Malvacearumpollis bakonyensis* Cenozone. Of these, lower two cenozones are considered to be of Eocene to Oligocene age and uppermost, *Malvacearumpollis bakonyensis* Cenozone represents Early Miocene age. Later, the study has been extended to Kalarakod and Nirkunnam borehole, Alleppey District (Rao, 1995) and to the surface exposure at Meenkunnu (Cannanore), Kundra–Kannanellur, Padappakkara and Varkala area (Rao, 2001) for lateral correlation and observed that the *Malvacearumpollis bakonyensis* Cenozone (Lower Miocene) in the borehole is correlated with lower part of the sections exposed on the surface (Rao, 1995, 2001). The major recorded tropical families are Schizaeaceae, Parkeriaceae, Osmundaceae, Adiantaceae, Polypodiaceae, Caesalpiniaceae, Clusiaceae, Ctenolophonaceae, Oleaceae and Rubiaceae. Fern spores and the tropical rain forest elements (Ctenolophonaceae, Oleaceae, Proteaceae and Moraceae) indicate high rainfall. The palynoflora assemblage indicates a humid and tropical climate with plenty of rainfall during the deposition of these sediments. It was also suggested that since Miocene time the climate pattern of Kerala region have not much changed (Ramanujam, 1987). Recently, Reuter *et al.* (2013) used pollen flora consist of 49 taxa belonging to 43 families (appendix 1) from Varkala Cliff section (Ambalapuzha Formation) as the direct proxy for monsoon over southern India during the Middle Miocene Climate Optimum.

The Quilon beds bear an important position in Indian stratigraphy, representing evidence of marine transgression

Table 1—A comparative chart of different stratigraphic classification scheme of Tertiary sediments, Kerala Basin, India (modified after Ramanujam, 1987).



Paulose & Narayanaswamy (1968)		**Raha *et al.* (1983); Raha (1996)**				
Recent to sub-recent Soils and alluvium, Beach sand deposits, lime shell deposits of backwaters, old and red Teri sands, peat beds with semi-carbonised woods, calcareous clays with shell etc., Laterite bed		***Vembanad Fm.*** Beach sand, sand clay with peat beds. Alluvium and gravel beds	**Quaternary**		MALABAR SUPER GROUP	
unconformity		*unconformity*				
Warkalli Fm. Current bedded friable variegated sandstone, carbonaceous clays, and lignite seams, gravel-pebble	**Late Miocene to Pliocene**	***Ambalapuzha Fm.*** Fluvial sandstone clays and lignite	**Mio-Pliocene**	**WARKALLI GROUP**		**TERTIARY**
Quilon Fm. Fossiliferous shell limestone alternating with thick beds of sandy clays, calcareous clays and sandstone, base unknown	**upper part Middle Miocene**	***Quilon Fm.*** Limestone, calcareous clays and sands	**Early-Middle Miocene**			
	lower part Early Miocene	***Mayyanad Fm.*** Fluvial sandstone, clay and lignite	**Early Miocene**			
unconformity		*unconformity*				
		Karuchal Fm. Hard, compact, ferruginous gritty sandstone with clay interbeds	**Early Eocene-Oligocene**			
unconformity		*unconformity*				
Archaean crystalline rocks						

along the south–west coast of India during Miocene, similar to the marine deposits along northwestern and western parts of the Indian subcontinent (Verma, 1977). Ostracods and palynological studies suggested depositional environment of these sediments ranges from marginal marine, brackish lagoon as well as brackish and freshwater swamps (Rao & Ramanujam, 1975; Rao, 1995). Further, the open marine shelf with coral reef, shallower than 20 m proximal to coast has also been opined for deposition of the Quilon Formation (Menon, 1967a, b; Raha & Sinha–Roy, 1982; Narayanan *et al.*, 2007). Recently, facies and faunal assemblage from the same formation suggested sea grass environment during marine transgression into marginal marine lagoons and swamps (Reuter *et al.*, 2011).

According to Rao and Ramanujam (1975) and Rao (1995), palynofloras and ostracod assemblages from Varkala Cliff (Ambalaphuzha Formation of Warkalli Group) indicate marginal marine, brackish lagoons and brackish and freshwater swamps. However, in the absence of age of the sediments, precise stratigraphical position and relationships, these depositional environment models cannot be discussed in terms of geological history of basin.

AGE AND TIME BOUNDARIES

Many attempts (Table 1) were made to establish time–stratigraphic relationship between Quilon and Warkalli beds of Neogene Period based on microfloral and faunal investigations since 1950's but still discrepancy continued (Soman, 2013). The Vaikom beds from subsurface borehole of CGWB, Kerala has been dated to Eocene to Oligocene. The foraminifers, ostracods, and mollusks recorded by Jacob and Sastri (1952) and Dey (1962) assigned an Early to Middle Miocene age to Quilon Formation. The overlying Warkalli Formation is dated to late Miocene to Pliocene in age (Poulose & Narayanaswamy, 1968). Several palynological studies have been conducted on the outcrop sections of Tertiary sediments from various localities (Rao & Vimal, 1953; Potonie & Sah, 1960; Ramanujam, 1977, 1987; Rao & Ramanujam, 1978, 1982; Kar & Jain, 1981) opined Early to Middle Miocene age to the

Table 2—Important palynofossils recorded from Neogene successions of Kerala Basin (compiled from Ramanujam, 1987; Singh & Rao, 1990; Rao & Nair, 1998; Rao, 2001; Reuter *et al.*, 2013; Kern *et al.*, 2013).

Family	**Palynotaxa**	**Modern comparable taxa**	**Quilon Formation**	**Warkalli Formation**
Pteridophytic spores				
Cyatheaceae	*Cyathidites*		●	●
	Alsophilidites		●	●
Dicksoniaceae	*Cibotiidites*		●	—
Gleicheniaceae	*Gleicheniidites*		●	—
Hippocrateaceae	*Hippocrateaceaedites*		●	●
Lycopodiaceae	*Lycopodiumsporites*		●	●
	Verrucosisporites	*Lycopodium*	●	●
Ophioglossaceae	*Foveosporites*		●	●
Osmundaceae	*Osmundacidites*		●	●
Parkeriaceae	*Striatriletes*		●	●
Pteridaceae	*Pteridacidites*	*Pteris*	●	●
Schizaeaceae	*Lygodiumsporites*		●	—
	Intrabaculisporis		●	—
	Crassoretitriletes	*Lygodium*	●	●
	Schizaeoisporites	*Schizaea*	●	●
	Neyvelisporites		—	●
	Verrutriporites		●	●
Angiosperm pollen				
		Monocotyledons		
Araceae	*Proxapertites*		●	●
Arecaceae	*Verrumonocolpites*		●	●
	Spinamonoporites		●	●
	Palmidites		●	●
	Longapertites		●	●
	Dicolpopollis	*Calamus*	●	●
	Quilonipollenites	*Eugeissona*	●	●
	Disulcipollis	*Metroxylon*	—	●
	Spinizonocolpites	*Nypa*	●	●
	Clavapalmaedites	*Oncosperma*, *Ceroxylon*	●	●
	Palmaepollenites	Palm	●	●
	Arecipites	Palm	●	●
	Neocouperipollis	Palm	●	●
	Paravuripollis	*Salaca*	●	●
	Trilatiporites	*Sclerosperma*	—	●
Iridaceae	*Iridacidites*	*Watsonia*	—	●
Liliaceae	*Liliacidites*		●	●

Poaceae	*Monoporopollenites*		●	●
	Graminidites		●	●
Potamogetonaceae	*Retipilonapites*	*Potamogeton*	●	●
		Dicotyledons		
Anacardiaceae	*Rhoipites*		–	●
Apiaceae	*Umbelliferoipollenites*		●	●
Apocyanaceae	*Diporites*		–	●
Aquifoliaceae	*Clavatricolporites*	*Ilex*	–	●
Araliaceae	*Araliaceoipollenites*		●	●
Bombacaceae	*Bombacacidites*		●	●
	Lakiapollis	*Durio*	●	●
	Cauveripollis		●	●
Caesalpiniaceae	*Trisyncolpites*		●	●
	Margocolporites	*Caesalpina*	●	●
Caprifoliaceae	*Cauveripollis*		●	●
Caryophyllaceae	*Caryophyllidites*		–	●
Casuarinaceae	*Casuariniidites*		●	–
Chenopodiaceae	*Polyporina*		–	●
	Chenopodipollis		–	●
Combretaceae	*Heterocolpites*	*Lumnitzera*	●	●
Asteraceae	*Compositoipollenites*		–	●
Ctenolophonaceae	*Ctenolophonidites*	*Ctenolophon*	●	●
Dipterocarpaceae	*Dipterocarpuspollenites*		●	●
Droseraceae	*Ornatetradites*		●	●
	Droseridites		●	●
Euphorbiaceae	*Crotonoidaepollenites*		●	–
	Crototricolpites		●	–
	Psilatricolporites		●	●
	Tricolpropollis		●	●
Gunneraceae	*Tricolpites*		●	●
Haloragaceae	*Haloragacidites*	*Myriophyllum*	●	●
Hymenophyllaceae	*Biretisporites*		–	●
Lamiaceae	*Retistephanocolpites*		●	●
	Polycolpites		●	●
Lecythidaceae	*Marginipollis*		●	●
Lentibulariaceae	*Neyvelipollenites*		●	●
Loranthaceae	*Gothanipollis*		●	●
	Loranthipites	*Dendrophthoe*	●	●
Malvaceae	*Malvacearumpollis*		●	●
Meliaceae	*Meliapollis*		●	●

Menispermaceae	*Retitriporites*	*Cissampelos*, *Cocculus*	–	●
Moraceae	*Triporopollenites*	*Artocarpus*	●	●
Myricaceae	*Myricaceoipollenites*		–	●
	Myricipites		●	●
Myrtaceae	*Myrtaceidites*	*Eugenia*, *Syzygium*	–	●
Olacaceae	*Anacolosidites*		●	●
	Retitricolpites		●	●
	Retitrescolpites		●	●
Onagraceae	*Triorites*		●	–
Plumbaginaceae	*Warkallipollenites*	*Aegialites*	–	●
Polygalaceae	*Polygalacidites*		●	●
	Psilastephanocolporites	*Xanthophyllum*	–	●
Polypodiaceae	*Polypodiaceaesporites*		–	●
	Laevigatosporites		●	–
	Pilamonoletes		●	●
	Polypodiisporites		●	●
Proteaceae	*Proteacidites*		●	●
Rhizophoraceae	*Paleosantalaceaepites*		●	●
	Zonocostites		●	●
Rubiaceae	*Cricotriporites*		●	●
	Favitricolporites		●	●
	Subtriporopollis		–	●
	Palaeocoprosmadites	*Coprosma*	●	●
	Retitriporites	*Randia*	–	●
Rutaceae	*Retitricolporites*	*Fagaropsis*	–	●
Sapindaceae	*Talisiipites*		●	–
	Cupaniedites		●	●
Sapotaceae	*Sapotaceoidaepollenites*	*Madhuca*, *Manikara*	●	●
Sonneratiaceae	*Florschuetzia*	*Sonneratia*	–	●
Symplocaceae	*Symplocoipollenites*	*Symplocos*	●	●
Thymeliaceae	*Clavaperiporites*	*Wikstroemia*	●	●
Tiliaceae	*Intratriporopollenites*		–	●
	Lacrimapollis	*Brownlowia*	–	●
undetermined	*Eximospora*		●	–
	Faveotrilites		●	–
	Cingulatisporites		●	–
	Spinainaperturites		●	–
	Clavainaperturites		●	–
	Crotonisulcites		●	–

Faveotricolpites	●	–
Punctatricolpites	●	–
Bacubrevitricolpites	●	–
Clavasyncolpites	●	–
Meyeripollis	●	–
Costatipollenites	●	–
Foveostephanocolporites	●	–
Padappakkarapollis	●	–
Polybrevicolporites	●	–
Echitriporites	●	–
Tetrapollis	●	–
Inaperturotetradites	●	–
Parsonsidites	●	–
Stephanocolpites	–	●
Clavatricolpites	–	●
Ranunculacidites	–	●
Pseudonothofagidites	–	●
Farsonsidites	–	●
Periporopollenites	–	●
Sparganiaceaepollenites	–	●
Intrapunctisporis	●	●
Dandotiaspora	●	●
Seniasporites	●	●
Cicatricosisporites	●	●
Scantigranulites	●	●
Cheilanthoidspora	●	●
Maculoporites	●	●

Quilon and Warkalli beds. However, most of the palynological studies have also not been related to stratigraphically located samples except a few (Ramanujam, 1987; Raha *et al.*, 1983; Rao, 1990, 1995). Raha *et al.* (1983, 1986, 1987), Rajendran *et al.* (1989), Rao (1990, 1995, 1996), Rao & Rajendran (1996) and Rao & Nair (1998) investigated the surface as well as subsurface Tertiary successions of Kerala basin. Palynological and foraminiferal studies suggested a complete succession of Early Eocene through Oligocene to Miocene in the subsurface in central part of basin. From the Ambalapuzha borehole, Raha *et al.* (1987) suggested that palynomorph taxa *Proxapertites microreticulatus, Polycolpites, Meliapollis ramanujamii, M. quadrangularis, Proteaeidites triangulus, Striacolporites cephalus* together with some palm pollen indicate an Eocene age. Oligocene age was inferred by the presence of *Crassoretitriletes vanraadshooveni, Trisyncolpites ramanujamii* and *Bombacacidites*. The occurrence of *Malvacearumpollis, Hibisceaepollenites splendus* and *Quilonipollenites* are indicative of an Early Miocene age. Whereas, Ramanujam (1987) noticed similarity in palynological assemblages of both the formations and concluded that the two formations pertain to a single time transgressive unit of Early to Middle Miocene age under different depositional environments.

Interestingly, in few studies (Rao, 1990, 1995; Rao & Rajendran, 1996; Rao & Nair, 1998) dinoflagellate cysts have been recorded but not considered for biostratigraphy and dating of the sedimentary successions. Recently, along with larger benthic and planktonic foraminifers from the type section of Quilon Formation and age diagnostic nannofossils

Sphenolithus belemnos and associates have been recorded and suggested the age of nannoplanktonic biozone NN3—~18–19 Ma (Reuter *et al.*, 2011). Interestingly, in the absence of marker fossils, only on the basis of order of superposition and conformable contact of Ambalapuzha Formation (Varkala cliff) with Quilon Formation late Burdigalian to early Langhian age have been deciphered (Reuter *et al.* 2013) for Ambalapuzha (Warkalli) Formation.

DISCUSSION ON PERSPECTIVE OF PALAEOCLIMATIC STUDIES

The Miocene Period is considered to be period of "making of the modern world" (Potter & Szatmari, 2009). The major uplift of modern mountain chains, the initiation of bipolar glaciations, the origin of modern ocean currents, the aridification of the continental interiors, the reduction in atmospheric CO_2 levels and the overall cooling trend of the global climate occurred in Miocene time (Zachos *et al.*, 2008; Potter & Szatmari, 2009; Beerling & Royer, 2011). Coupled with these key climate changes profound global vegetation changes occurred such as expansion of grassland and C4 plants in late Miocene (Quade *et al.*, 1989; Cerling *et al.*, 1997; Jacobs *et al.*, 1999; Strömberg, 2002).

By the start of the Neogene, the Indian Plate was firmly sutured to the Eurasian Plate. The northward movement of the Indian Plate, followed by the gradual uplift of the surrounding terrain and the retreat of the Tethys, is archived in the Neogene sedimentary record of northern India such as the Trans Himalayas, Himalayan foreland basin and Sulaiman Province of Pakistan. The thick piles of sediments were deposited by the Indo–Gangetic river systems due to crustal shortening and the rise of the Himalayas and sinking of the foreland basin. A number of proxy records including palaeosols (Retallack, 1995; Thomas *et al.*, 2002), soil carbonates (Quade *et al.*, 1989; Sanyal *et al.*, 2004, 2005a, b, 2010), microfossils (Phadtare *et al.*, 1994; Hoorn *et al.*, 2000), palaeomagnetism (Sangode & Bloemendal, 2004) and general sedimentation pattern have been used to decipher the changes in the Indian summer monsoon from the Siwalik sediments. With the help of $\delta^{18}O$ value Quade *et al.* (1989, 1995), Kroon *et al.* (1991), Stern *et al.* (1997) and Sanyal *et al.* (2004, 2005b) suggested intensification of the Indian summer monsoon at 10.5, 5.5 and 3 Ma. Additionally, Himalayan foreland basin sediments recorded the appearance of C4 plants over a period of 9 to 6 Ma (Quade *et al.*, 1989, 1995; Sanyal *et al.*, 2004, 2005a) which is closely linked to the monsoon dynamic in the Indian subcontinent. With changes in geodynamics and climatic setup, retraction of Paleogene tropical megathermal rainforest and evolution and expansion of Neogene subtropical deciduous vegetation types occurred in different parts.

The Neogene strata in north east India are identified as Surma and Tipam groups. Several publications dealing with palynology provide the evidence of tropical to subtropical vegetation during Oligocene–Miocene in NE India (Banerjee *et al.*, 1973, Saxena *et al.*, 1987; Kar, 1990; Kar *et al.*, 1994; Kumar *et al.*, 2001, 2012; Mandaokar, 2002a, b). The quantitative palaeoclimate reconstruction based on megaflora indicated a monsoonal climate during this period with the same intensity as that of modern day (Srivastava *et al.*, 2012). In the western India, a large part of Gujarat State was occupied by shallow sea during Neogene where terrestrial remains were preserved in association with marine biota in Kutch. The sedimentological data from the type locality of Oligocene in Kutch suggested an active monsoon over the Eastern Tethys and recorded tropical cyclone activity along the NW Indian coast during the late Oligocene warming period (~27–24 Ma). Early Miocene of Kutch (Mandal, 2010; Verma *et al.*, 2013) and other sites in Gujarat and Rajasthan (Shukla *et al.*, 2013) indicate the presence of wetter conditions with warm and humid tropical rainforests. In southern India, the palynological studies on Miocene deposits have been conducted in Krishna–Godavari Basin (A.P.), Cauvery Basin including Neyveli Lignites (Tamil Nadu), Sindhudurga Formation (Maharashtra) to infer vegetation of past. The detailed reviews of palynological studies of Miocene of India have been discussed by Saxena and Tripathi (2012) and Rao and Verma (2014).

From the perspective of palaeoclimatic studies, the Varkala cliff section has been studied to ascertain the effect of MMCO warming on the monsoonal pattern in the region (Reuter *et al.*, 2013; Kern *et al.*, 2013). Based on Coexistence approach applied to pollen flora, Reuter *et al.* (2013) suggested modern–like monsoonal precipitation pattern contrasting to inferences drawn from marine records (Clift *et al.*, 2008; Wan *et al.*, 2010). Further, the strength of monsoon is not linked with global warming and atmospheric conditions over Tibetan Plateau. But later, Kern *et al.* (2013) revised the results and presented different coexistence interval that suggested significantly lower values for the mean annual precipitation with distinct seasonality pattern. Kern *et al.* (2013) also suggested the palaeovegetation over south India was more uniform during Early to Middle Miocene as compare to today and no west–east gradient in rainfall persisted over southern India. Also, this reconstruction fails to explain the role of the Western Ghats, which already existed by that time (Pande, 2002; Gunell *et al.*, 2003), in Indian monsoon rainfall distribution over south India. Moreover, the low taxonomic resolution of plant determination at family level cannot detect genera/species adaptation to change in climate.

The isotope studies from Miocene limestone of the Quilon Formation show a warmer climate with an average value of 34.25°C and down core decrease, ^{13}C values been correlated with sea level rise during Miocene in which the limestone got deposited (Narayanan *et al.*, 2007). Interestingly, in the absence of precise age model and stratigraphic uncertainties, these reconstructions of climate are not very convincing and needed the further precise study. Rather, concerted efforts are required for systematic study of the entire Tertiary deposits of Kerala Basin to provide biostratigraphic framework and age model. Further, palaeofloral data is needed to understand the early history of Indian monsoon and response changes of flora in respect to major phases of palaeoclimate evolution such as MMCO.

CONCLUSIONS

The review suggests that palynological assemblages of Quilon and Warkalli consist of rich assemblage of fungal remains, pteridophytic spores, and angiospermous pollen indicate a humid and tropical climate with plenty of rainfall during the deposition of these sediments.

The recorded palynotaxa including mangrove elements and dinoflagellate cysts indicate marginal marine environment of deposition ranging from back swamp, tidal to sub–tidal zones in which evergreen forest along with rainforest elements from hinterland were getting deposited. However, utilization of dinoflagellate cysts has been overlooked as proven valuable proxy for biostratigraphy, age model, and good palaeoecological indicator.

The onshore surface and subsurface Cenozoic sedimentary successions of Kerala Basin offer a great potential to study palaeoclimatic conditions such as of global climatic events of Neogene (Mid Miocene Climate Optimum at ~17–15 Ma) and even of older times Eocene–Oligocene transition of southwest India.

Using the palynoflora as the direct proxy for climate change, the quantitative climate reconstructions should be done in terms of past temperature, precipitation, and seasonality over southern India during Neogene.

The review also suggests, the entire Cenozoic sequence of Kerala Basin is needed to be restudied palynologically both from the surface and subsurface on finer resolution with aim to the build biostratigraphy and age model that can provide substantial time–constrained palaeoclimatic changes.

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