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Primary productivity and organic matter distribution during SW and NE monsoon from Alleppey mudbanks, Kerala, India

Biswajeet Thakur*, Vandana Prasad and Rahul Garg
Birbal Sahni Institute of Palaeobotany, 53, University Road, Lucknow 226 007, India

Formation of mudbank during summer monsoon and its dissipation during winter is a characteristic feature of the southwest coast of Kerala, South India. Both southwest (SW) and northeast (NE) monsoons play an important role in the overall run-off-related changes and sedimentation pattern in this region that governs the primary productivity in the region. The present study is an attempt to assess primary productivity and precipitation-induced run-off-related changes using biotic proxies (diatoms and palynofacies) during NE and SW monsoons, from the surface sediments of the Alleppey mudbanks along Kerala coast. ANOVA test was performed on diatoms and palynofacies to assess their significance during both monsoonal periods. The study provides a significant insight into the monsoon-controlled palynofacies distribution behaviour pattern that attests to the concept of precipitation-induced high run-off during SW monsoon being the governing factor in the formation of mudbanks in this region.

Keywords: Diatoms, monsoons, mudbank, palynofacies, primary productivity.

THE state of Kerala, situated on the southwest coast of the Indian subcontinent, is bestowed with 41 westerly-flowing rivers and estuarine complexes with a coastline extending for more than 560 km. The formation of mudbanks during the southwest (SW) monsoon period is a unique phenomenon that is exhibited at certain locations along the coastal region (Malabar coast) of Kerala[1,2] (Figure 1). The Alleppey region along the Malabar coast experiences formation of mudbanks during the SW monsoon period[3]. Mudbanks are patches of calm, turbid water with heavy suspended load of clay-size particles less than 1 μm in size[2,4]. The historical record of Alleppey mudbanks is known since 1885, the formation of which is an annual phenomenon during June to August[5]. The geographical extent of the mudbanks and their nature and formation based on sediment characteristics have been discussed in detail, demonstrating fine deposition of silt and mud[6–9]. The phenomenon of coastal upwelling for mudbank formation is regarded to be one of the major factors along the Malabar coast, Kerala[10]. Mudbank formation by run-off-induced activity and coastal upwelling during monsoon

*For correspondence. (e-mail: biswajeet_thakur@yahoo.co.in)

fluctuations has been documented on sedimentary and geochemical evidences by earlier workers[11–16]. The region experiences a warm and humid climate with mean annual temperature ranging between 18°C and 30°C during both the SW (summer) and NE (winter) monsoons with annual precipitation of approximately 2763 mm. During the summer monsoon the precipitation is approximately 1819 mm and during the winter monsoon it is 589 mm (ref. 17).

Alleppey lies on the coastal zone of Kerala intercepted by lagoons and monsoon-fed rivers (Figure 1). Theories regarding formation of mudbank include mudflow from the backwaters by hydraulic pressure through subterranean channels in the narrow strip of land that separates the backwaters from the sea or through discharge of large detritus by the rivers[18]. The nearshore sediment dynamics during the monsoon period provides evidence to the *in situ* phenomena for the formation of mudbanks[19,20]. High biological productivity in the mudbanks provides rich fishery grounds[3,21] with wave energy minimizing coastal erosion so common elsewhere on the SW Indian coast[15,20,22,23]. Little data are available on primary productivity and organic matter distribution pattern based on palynofacies and diatoms during both SW and NE monsoon regimes of Alleppey mudbanks apart from that known from sedimentary and geochemical proxies[12,20]. The palynofacies and diatoms tool collectively provide a firm basis to understand the run-off-related changes, productivity signals and shoreline fluctuations due to seasonality effect in monsoonal precipitation in the mudbank region. Diatoms are microscopic, unicellular algae that are known constituents of the base of the food chain and are a major source of primary productivity in the oceans[24–26]. Palynofacies is a useful proxy tool to decipher depositional environment in shallow marine and coastal regions. The organic matter in marine sediments accumulates from both allochthonous and autochthonous sources[27]. The distribution of the former is controlled mostly by the physical process, and the latter is influenced by the biological/ecological processes along with the hydrodynamic conditions[28]. Palynofacies studies primarily help in the characterization and quantitative estimation of both allochthonous and autochthonous organic matter components to infer run-off and productivity-related changes[29]. The distribution of dispersed organic matter in shallow marine sediments is well studied along other regions of the Kerala coast[30–34], but such studies are yet to be carried out in the Alleppey mudbanks. The present study is an attempt to compare the diatom assemblages and palynofacies characteristics in surface sediments collected from mudbanks near Alleppey coast during both SW and NE monsoon periods.

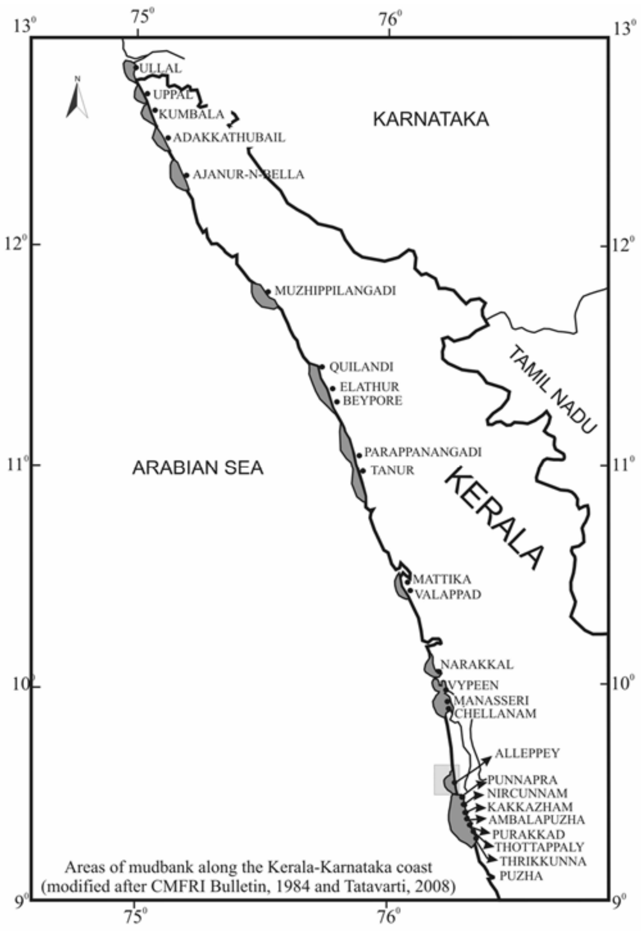

Figure 1. Location of mudbanks in Kerala.

Surface sediment samples were collected during July 1983 using Petersen grab from stations 1 to 16 in the coastal region of Alleppey and Mararikulam South at different isobaths (5, 6, 7, 8, 9, 9.75 and 11 m; Figure 2). The second set of surface sediment samples was collected during December 1983 from the same stations and along the same depth transects (Figure 2). The samples were procured from the repository of the Birbal Sahni Institute of Palaeobotany, Lucknow. For the diatom extraction the method of Battarbee[35] was followed. For identification and counting of the diatoms, frustules classification of Round *et al.*[26] was followed. For the palynofacies studies palynological preparation technique[29] has been employed and sedimentary organic matter has been studied based on the earlier described procedures[29,34,36] (Table 1).

In the mudbanks of Alleppey and Mararikulam South, the diatom assemblages are marked by dominance of freshwater forms over marine diatom species (Figures 3 and 4). The freshwater diatom assemblage comprises both centric and pennate forms, e.g. *Cyclotella meneghiniana*, *Navicula* spp., *Stauroneis* sp., *Nitzschia palea*, *Surirella* sp., *Cymbella silesiaca* and *Pinnularia gibba*. The marine diatoms represented by *Diploneis didyma*, *Thalassiosira* sp., *Triceratium favus*, *Actinocyclus ingens* and *Actinoptychus* sp. show relatively lower frequency (Figures 3 and 4). Amongst freshwater diatoms, *Cyclotella* and *Navicula*

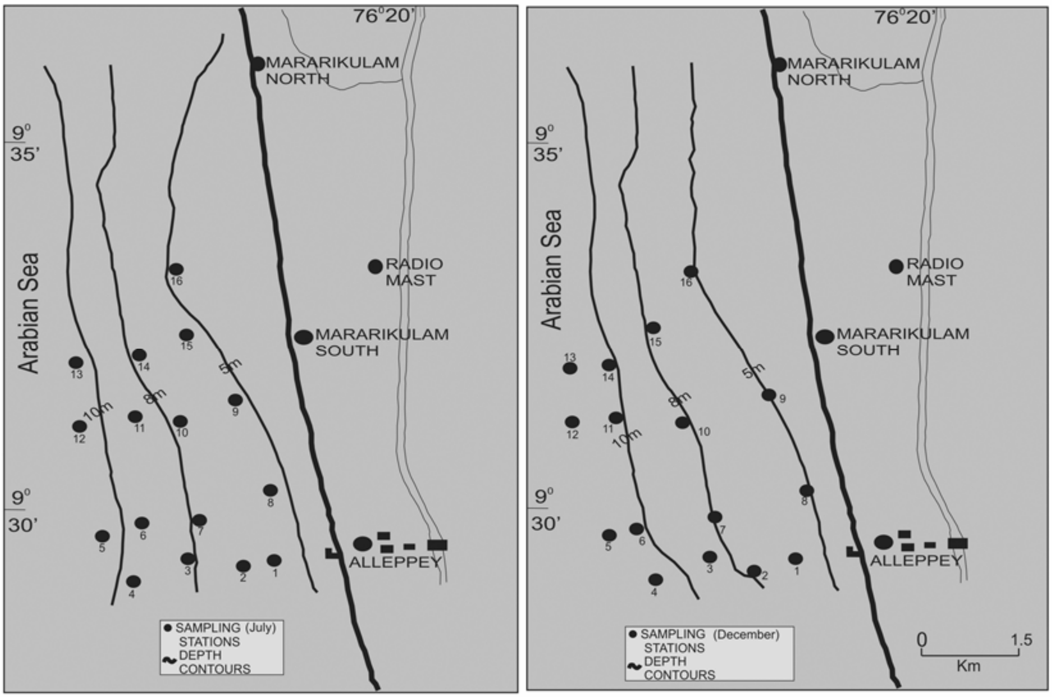

Figure 2. Sample site locations of Alleppey mudbanks.

Table 1. Sedimentary organic matter distribution

Group	Category	Characteristics features and origin
Palynodebris	Black oxidized	Oxidized land plant tissue
	Degraded brown	Partially degraded land plant tissue
	Structured	Well-preserved land plant tissue
	Amorphous	Unstructured homogeneous material of marine origin
Palynomorphs	Peridinioid dinocyst	Primary consumers, marine origin
	Gonyaulacoid dinocyst	Primary producers, marine origin
	Cyanobacteria	Primary producers, freshwater and marine origin
	Tintinnids	Secondary consumers, marine origin
	Scolecodonts	Mouth parts of predominantly planktonic annelids, marine origin
Zooplanktonic remains	Copepods	Egg envelopes of copepod egg, marine origin
	Labile organic matter	Transparent exoskeleton fragments (various shapes) of planktonic crustaccans, marine origin
	Foraminiferal test lining	Marine origin

spp. dominate in samples collected during both seasons, contributing up to 80% of the diatom assemblages in all stations (Figures 3 and 4). However, their frequency is comparatively higher in samples collected during the SW monsoon period. The rest of the freshwater diatoms contributed about 15–18% of the total diatom population. The freshwater diatoms show a significant distribution pattern with higher frequencies in the coastal region and much reduced frequency in offshore area (Figures 3 and 4). The diatom count of *C. meneghiniana* species was higher along the Alleppey region, but towards the north along Mararikulam South the frequency decreased and was replaced by the *Navicula* spp. in July (Figures 3 and 4). The diatom *Stauroneis* shows high counts along the coastal isobaths, but decreased significantly at the intermediate depths (8–9 m), and again increased in the offshore regions (11 m) during both the monsoonal period (Figures 3 and 4). The distribution of *Surirella*, *Nitzschia palea* and *C. silesiaca* was negligible accounting for less than 2% of the overall diatom population during both monsoons (Figures 3 and 4). Amongst marine diatoms, *Thalassiosira* is the dominant form; the frequency increases off the coastal region and attains its peak at depths 9 and 11 m (Figures 3 and 4). The frequency of *Thalassiosira* is reduced to nearly half during the NE monsoon compared to the SW monsoon (Figures 3 and 4)

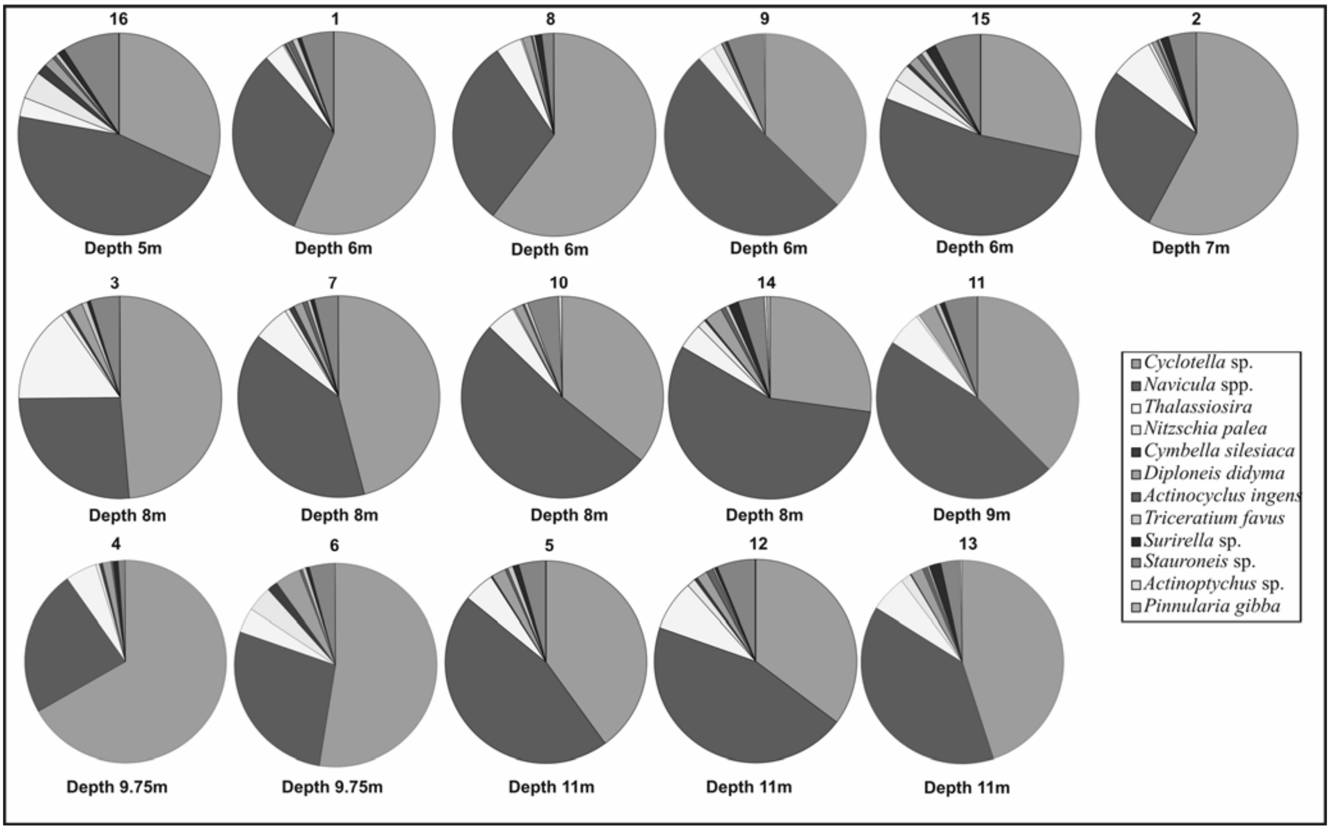

Figure 3. Pie chart for July diatoms distribution.

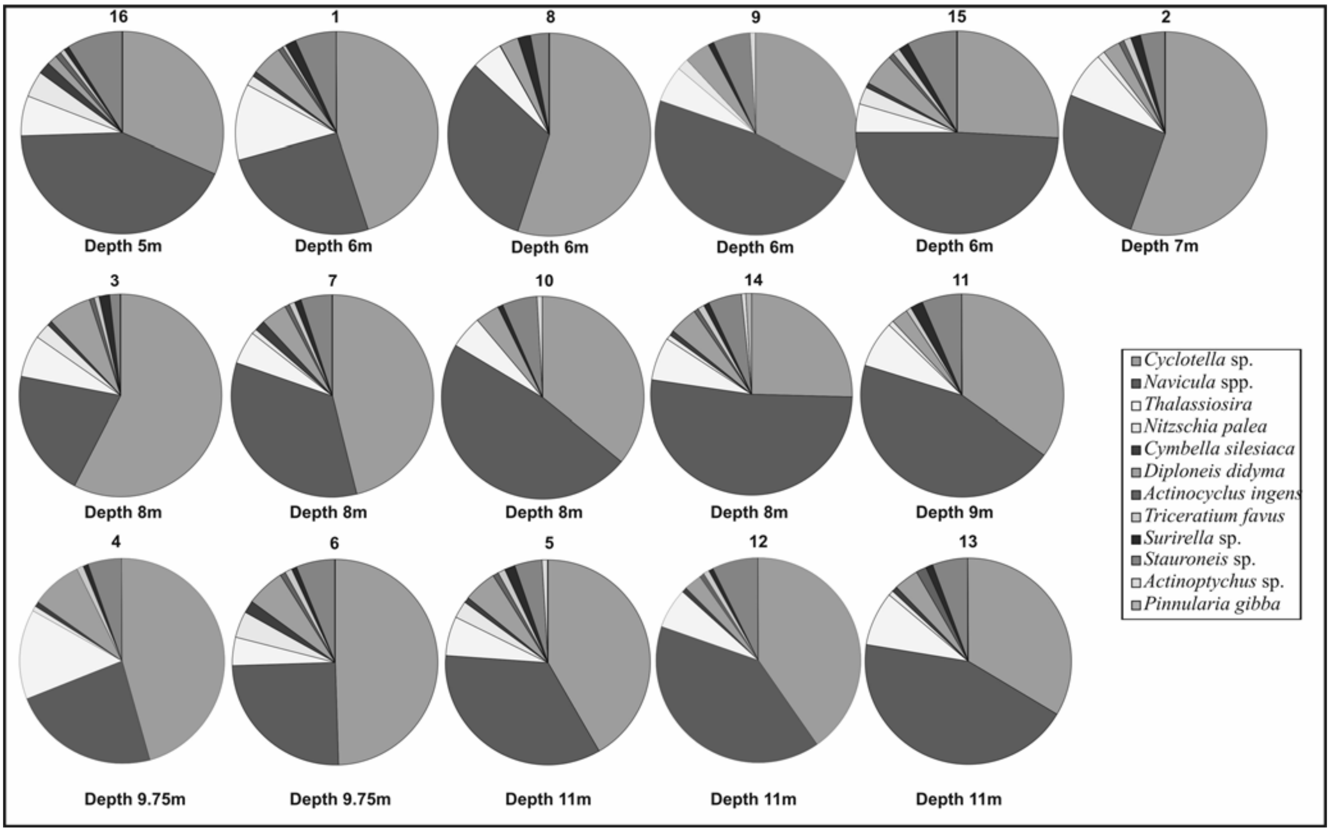

Figure 4. Pie chart for December diatoms distribution.

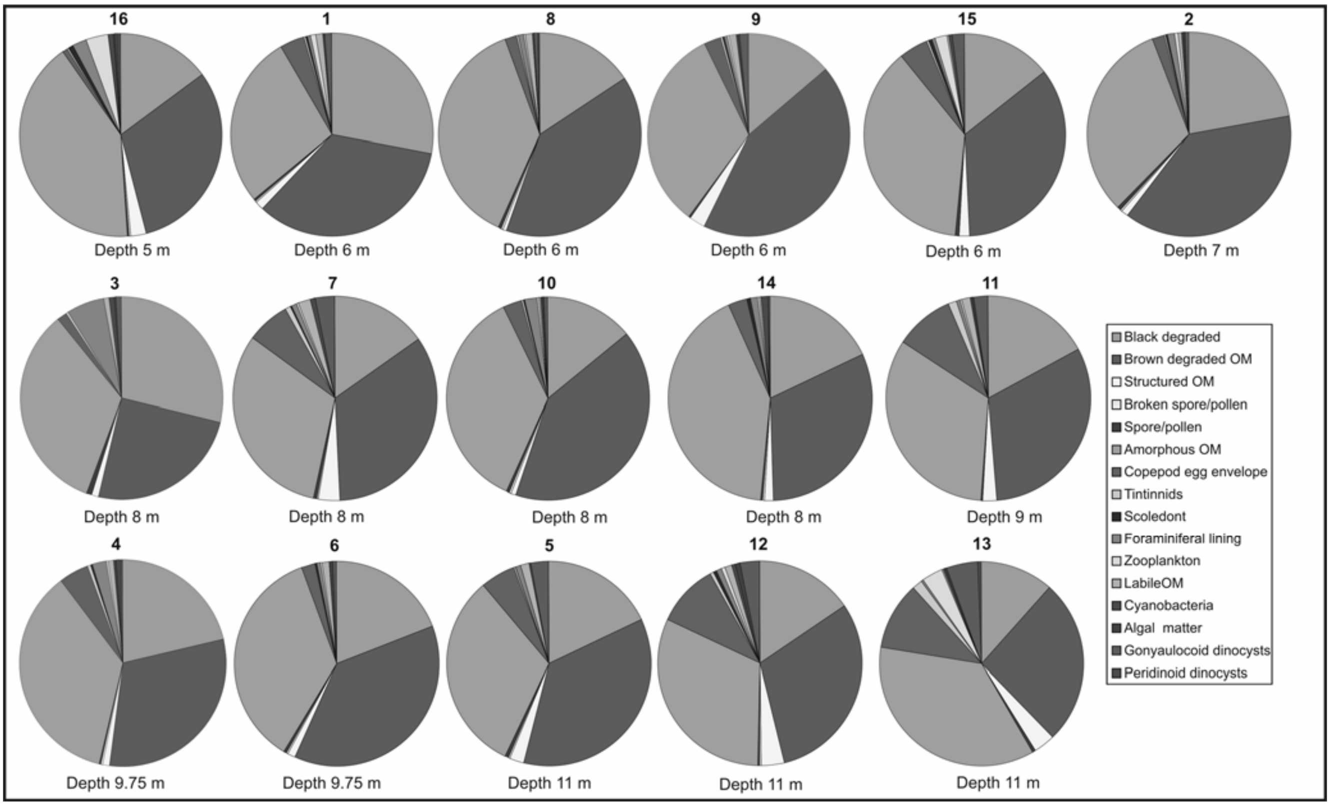

Figure 5. Pie chart for July palynofacies distribution.

probably due to reduced productivity. The pennate diatom *Diploneis didyma* was present at all the stations in both seasons, whereas *A. ingens*, *T. favus* and *Actinoptychus* were found only during the SW monsoon (Figures 3 and 4).

Palynofacies distribution in the mudbanks of the Alleppey region reflects a significant pattern related to coastal and marine production, preservation and degradation of organic matter. Palynofacies assemblages at all stations show dominance of high influx of terrestrially derived organic matter components over the marine-derived elements. The terrestrially derived components comprise about 65–70% of the total palynofacies components (Figures 5 and 6). The terrestrially derived palynofacies components show abundance of brown degraded organic matter followed by the black oxidized organic matter. The structured debris, pollen/spore and cyanobacteria occur in very low frequencies (Figures 5 and 6). The marine-derived palynofacies components are marked by the presence of high amounts of amorphous organic matter followed by copepod egg envelopes, foraminiferal test linings, zooplankton, scolecodont, tintinnids and labile organic matter (Figures 5 and 6). In the Alleppey mudbanks, the terrestrially derived organic matter predominates in the samples of SW monsoon compared to those of NE monsoon (Figure 5). However, sorting of terrestrial organic matter is higher in the NE monsoon samples as indicated by the dominance of well-sorted charcoal and degraded organic matter content. In the intermediate depths from 7 to 9 m, brown degraded component is observed to be lower in the samples collected during both monsoon periods, and much reduced frequency is noted in the offshore region (Figures 5 and 6). The black oxidized organic matter shows high frequency during the SW monsoon, but at some stations the frequency is similar during both monsoon periods (Figures 5 and 6). Low counts of structured organic matter are present at all the stations; however, its dominance is mainly recorded in samples from the SW monsoon season. The pollen/spore and cyanobacteria occur in very low numbers at most of the stations and are absent at a few stations during the NE monsoon. The marine amorphous organic matter along with copepod egg envelopes, scolecodonts and tintinnids, show high dominance during the SW monsoon at all the stations (Figure 5). The distribution of foraminiferal test linings, zooplankton and labile organic matter which occur sporadically at most of the stations does not show any remarkable variation during both monsoon regimes. The dinoflagellate cysts contribute only 5% of the overall population of the organic matter. *Bitectatodinium spongium* is present at all the stations during SW and NE monsoonal periods.

In the present study, palynofacies assemblage and diatoms population were studied in samples collected during both SW (July) and NE (December) monsoons. The palynofacies study has an advantage in nearshore or coastal

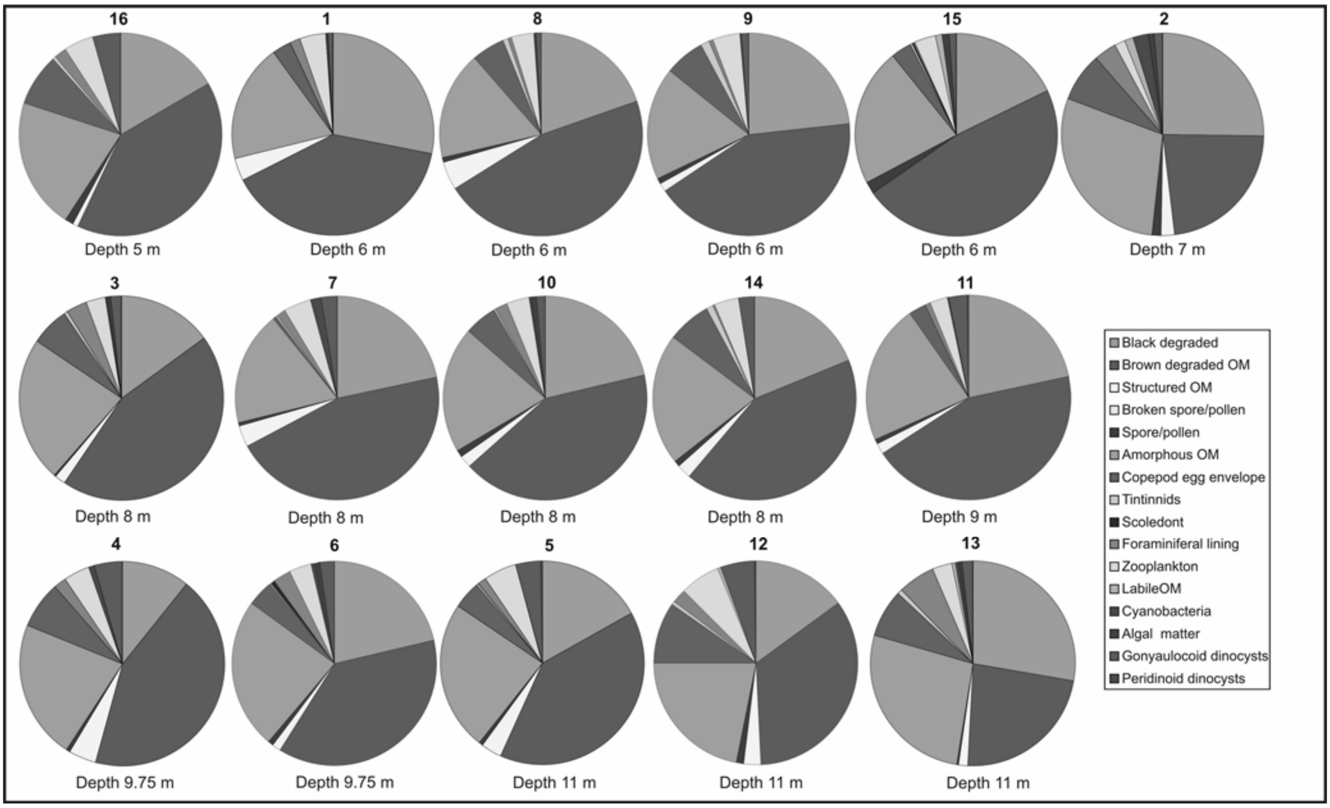

Figure 6. Pie chart for December palynofacies distribution.

regions as it helps identify the source and constituents of particulate organic matter assemblages[30,33,37,38]. The variation of palynofacies and diatoms in the Alleppey mudbanks was studied using Analysis of Variance (ANOVA) test to study the role of run-off-related precipitation activity during both monsoons. ANOVA is a statistical technique for assessing how nominal independent variables influence a continuous dependent variable. ANOVA is a statistical tool that is used to compare multiple groups of observations, all of which are independent but may have a different mean for each group. In the present study ANOVA was performed based on frequency of palynofacies and diatoms and to unravel the response of the palynofacies and diatom components in the mudbanks because of precipitation changes during SW and NE monsoons. Out of 14 palynofacies components, 10 were found to be significant based on ANOVA test (Figure 7), whereas in the case of diatoms only for 5 species significance can be rooted. The distribution and variation in the palynofacies components during both the monsoon periods provide evidence of variability in the run-off and primary productivity. During both the monsoon periods the frequency of the terrestrial components, viz. brown degraded, black oxidized and structured organic matter was high compared to marine organic matter and this was also found significant using ANOVA test ($P < 0.000$), suggesting that enhanced monsoonal precipitation during the SW monsoon incurred high run-off with much higher transport of terrestrial palynofacies components compared to the NE monsoon (Figure 7). In the rain gauge data we can obtain information about precipitation only for the past few decades, but the development of palynofacies and diatoms proxies can be useful for much older geological past. These studies backed by ANOVA analysis can provide vital clues for past precipitation changes and biotic distribution patterns in the depositional environment. However, sorting of terrestrial debris is noted to be higher during the NE monsoon, indicating the influence of current activity under high-energy conditions during deposition of the sediments. The ANOVA analysis for the marine components was found significant for amorphous organic matter, dinoflagellate cysts, copepods egg envelopes, zooplanktons, scolecodonts, cyanobacteria, algal matter and labile organic matter during the SW monsoon ($P < 0.000$; Figure 7) giving strength in support of high run-off conditions during SW monsoonal period. The high counts of marine components during SW monsoon are significant. Amongst the dinoflagellate cysts recorded in the sediments, high proportion of gonyaulacoid dinoflagellate cyst, *Bitectatodinium spongium* during SW monsoonal regime is indicative of high precipitation, and warm and humid climatic condition[39]. This makes it important as it shows the boundary of the marine organic productivity in the coastal and offshore regions in terms of productivity signals as well as monsoonal influx.

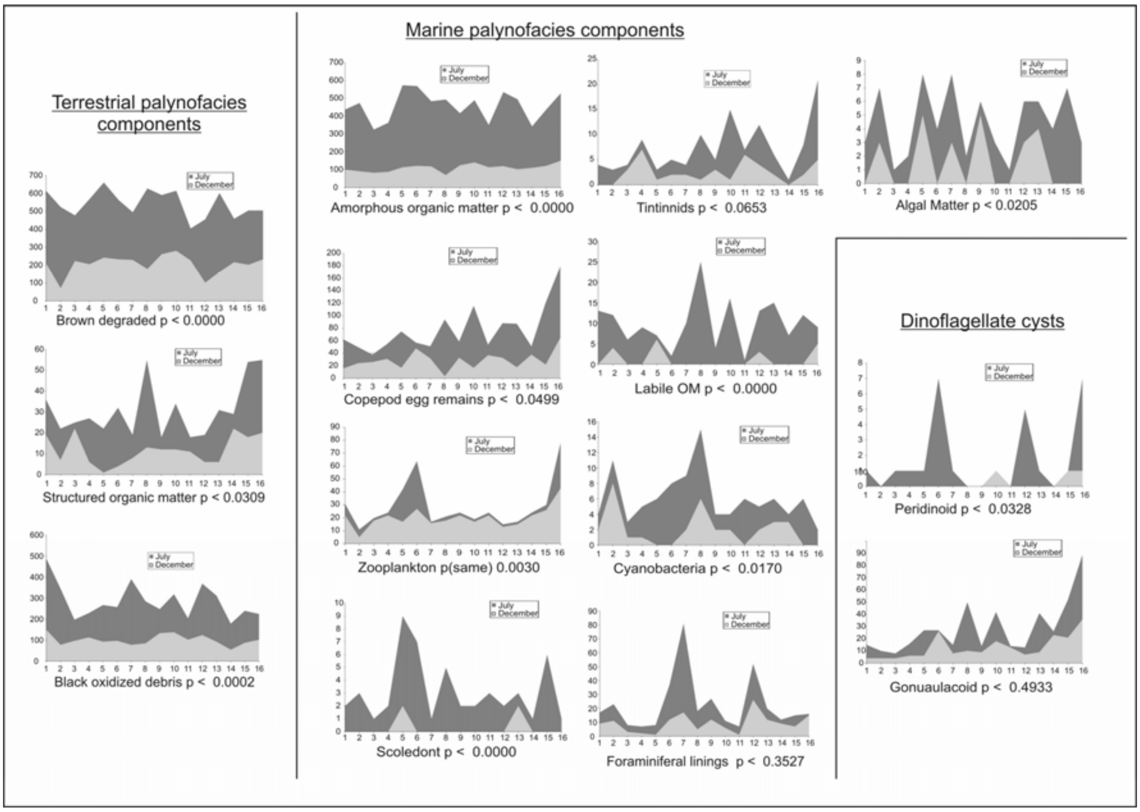

Figure 7. ANOVA graph for palynofacies distribution.

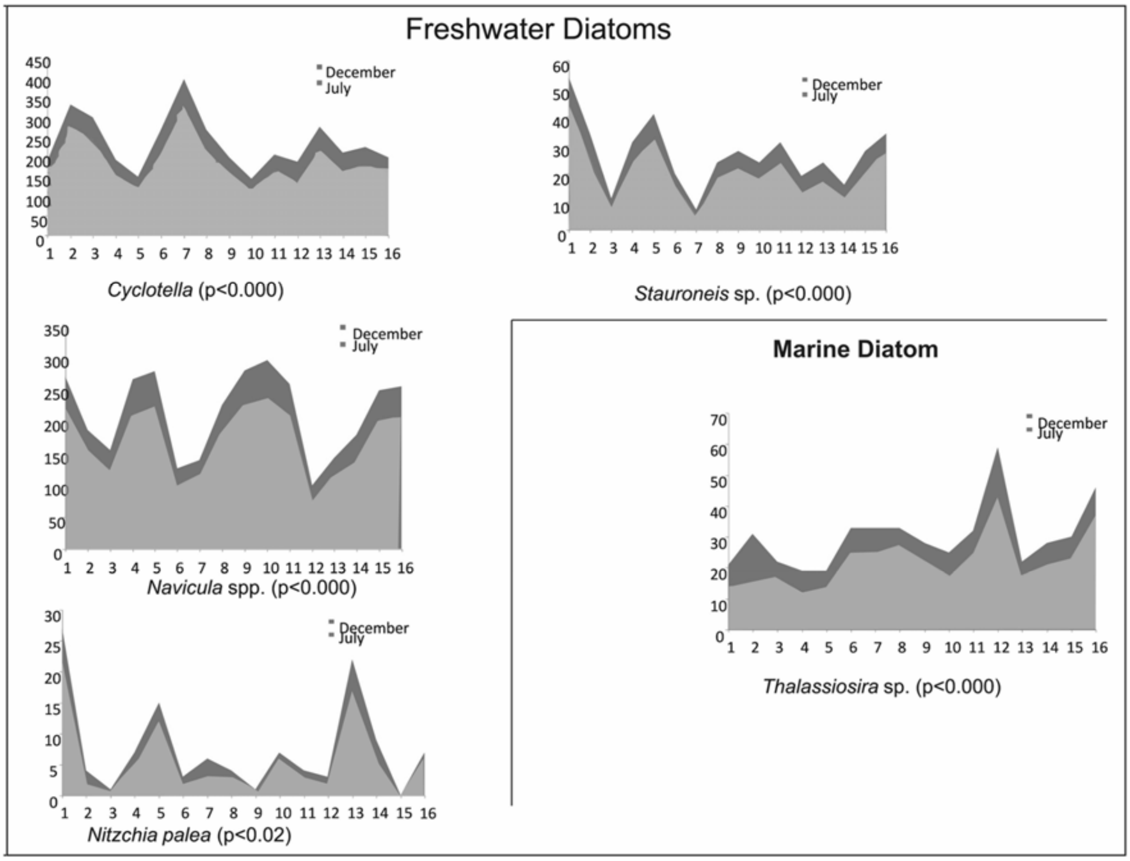

Figure 8. ANOVA graph for diatoms distribution.

The abundance of freshwater diatoms compared to marine forms during SW monsoonal period being indicative of high run-off has also been observed based on chlorophyll studies[40]. ANOVA was performed on diatom counts, demonstrating the significance of centric and pennate forms (Figure 8). The data show that the centric and pennate forms were comparable for both the monsoons (Figure 8). The presence of freshwater and brackish diatoms was found to be higher compared to marine diatoms during the SW monsoon. It is surmised that the high freshwater run-off increased the nutrient level and considerably lowered the salinity conditions suitable for the freshwater and brackish water diatom productivity. The diatoms *Cyclotella* and *Navicula* (both freshwater) show significance for ANOVA test, i.e. ($P < 0.000$), which confirm the Levene's test for homogeneity of variance (Figure 8). Stations close to the Mararikulam South reflect low relief and low energy environmental setting. The diatom population in this region shows higher counts of *Navicula* species.

The marine forms play a vital role in governing the distribution of diatoms along 8–11 m isobaths. Amongst them, *Thalassiosira* and *D. didyma* occur in significant numbers, though their density was found to be lower compared to freshwater forms. *Thalassiosira* showed significance in ANOVA test ($P < 0.000$) which confirms Levene's test for homogeneity of variance, but *D. didyma* did not respond in the ANOVA test, probably due to poor preservation as most of the similar forms were found to be broken. The freshwater pennate diatoms with lower frequency are represented by *Stauroneis*, *N. palea*, *Surirella*, *Cymbella* and *P. gibba* species. Occurrence of *Stauroneis* and *Nitzschia* is noted to be higher during the SW monsoon compared to the NE period. These forms are indicative of turbidity in the freshwater horizon and thus may reflect hydrodynamic conditions[41,42]. The low records of marine diatoms *T. favus* and *A. ingens* indicate warmer conditions, as they occur in the temperature range between 16°C and 24°C during the summer monsoon[43].

On the basis of diatoms and palynofacies studies of the mudbank sediments it can be concluded that the palynofacies criteria along with studies on diatoms can be a useful proxy to decipher primary productivity and run-off-induced palaeoenvironmental changes, particularly in coastal, shallow marine regions.

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Occurrence of rhyolite in Jangalgali Formation, Jammu and Kashmir, Northwest Himalaya, India

N. Siva Siddaiah* and M. K. Shukla

Wadia Institute of Himalayan Geology, 33, General Mahadeo Singh Road, Dehra Dun 248 001, India

We report here the occurrence of rhyolite between the Neoproterozoic Sirban Limestone and Palaeogene Subathu Formation in Northwest Himalaya, India. It is 5–10 m thick, consists of phenocrysts of quartz and feldspars of different shapes and sizes distributed randomly in a glassy matrix. Zircon, rutile, biotite, tourmaline and haematite occur in minor amounts. Bipyramidal, angular and skeletal morphologies are common in quartz. Quartz shows resorption features and contains inclusions of negative crystals. The field feature, mineralogy, texture and whole-rock composition are typical of high-silica rhyolites. By virtue of its occurrence at the base of the Himalayan foreland stratigraphy, the rhyolite is important in exploring the timing of India–Eurasia primordial collision and in stratigraphic correlation studies.

Keywords: Himalayan foreland basin, Palaeogene Subathu Formation, rhyolite.

THIS study reports the occurrence of rhyolite between the Neoproterozoic Sirban Limestone and Early Palaeogene Subathu Formation in Jammu region, Jammu and Kashmir (J&K) Himalaya, India (Figure 1)[1]. The lithounits sandwiched between Sirban Limestone and Subathu Formation in J&K are known as Jangalgali Formation and/or Khairikot Formation consisting of bauxite/laterite, rhyolite in addition to chert and variegated shale[2,3]. Although several biostratigraphic studies have been carried out on syn-orogenic sediments of the Subathu Formation because of their abundant and well-preserved fauna and hydrocarbon potential[4–10], there are no systematic studies on the lithounits that make up the Jangalgali Formation. Characterizing and determining the origin and age of the rocks of the Jangalgali Formation is important for a variety of reasons, including understanding their relation, if any, to India–Eurasia initial collision. As part of this objective, we present here results of our studies on the geological occurrence, field features, mineralogy and textural characters of silicic units of the Jangalgali Formation which were described in the literature as 'chert breccia', demonstrate their rhyolitic nature and discuss their importance in the Himalayan orogeny.

Regional geology and stratigraphic relations among Sirban Limestone, Subathu Formation and Jangalgali

*For correspondence. (e-mail: nssiddaiah@rediffmail.com)