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Textural and Mineralogical Characteristics of Silica Sand Deposits of Alappuzha-Cherthala Belt, Kerala, Southwest India

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Abstract

The coastal lowlands of Kerala in southwest India are endowed with deposits of fluvial and marine and aeolian mineral resources. Kerala's beach placers are a major and strategic mineral source in the area. Apart from beach placers, the coastal area in and around Alappuzha district has vast amounts of silica sand that occur between the Vembanad Lake and the seashore, spanning for about 35 km from Cherthala to Arookutti. Although many studies have been carried out on Kerala's beach placers, studies on silica-sand deposits of Alappuzha-Cherthala belt are very limited. Therefore, the present study addresses the textural and mineralogical characteristics of the Alappuzha-Cherthala belt. Fine sand comprises 11.2% to 57.3% in the surface sediments, while in the subsurface samples fine sand varies from 25.66% to 66.5%. Both the surface and subsurface sands are moderately to well sorted. These sands are in general coarsely skewed and leptokurtic. The mineralogical analysis reveals that opaques, sillimanite, and zircon dominate in the heavy mineral assemblage. The CM pattern revealed that the sands were generally transported by rolling and suspension. High sillimanite concentrations in the samples suggest a sialic metamorphic origin for silica sands. Long beach currents carried sillimanite and quartzose sands from the coastal extents of the Trivandrum Block in the south (south of Achankovil lineament) towards the Alappuzha-Cherthala coast, which is later modified into the silica sand deposits during the aridity event in the beginning of Late Holocene.

Keywords: Silica Sands, Alappuzha-Cherthala belt, Heavy minerals, Granulometric analysis, CM pattern

Introduction

The determination and interpretation of grain size characteristics of sediments and sedimentary deposits play an integral part in the understanding of their depositional mechanisms and environmental discrimination (Friedman and Sanders, 1978). The extent of sediment transport of both the ancient and the present sedimentary deposits can be determined using the analysis of particle size classes. Additionally, there is a significant body of evidence that grain size can vary in relation to channel shape, source materials, weathering and abrasion, and also due to sediment sorting during transport and deposition phases (Folk and Ward, 1957; Bridge, 2009). The image of the grain size spectrum obtained from granulometric analysis, along with the statistical characteristics derived from the size distribution, is commonly employed as primary tool to decode the energy regime that was prevalent during the transportation and deposition of sedimentary deposits (Folk, 1966; Friedman, 1967; Blatt *et al.,* 1972; Sly *et al.*, 1982).

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Furthermore, the textural characteristics together with heavy mineral assemblages of sedimentary deposits can provide better insights into the provenance as well as the extent of weathering at the source area (Padmalal, 1992; Padmalal and Seralathan, 1993; Badarudeen, 1997; Daurabh *et al.,* 1998; Arun *et al.,* 2019; Padmalal *et al.,* 2025). Additionally, it is one of the excellent tools in the paleogeographic reconstruction as well. Several researchers have determined the heavy mineral composition of beach sands from different locations along the Indian coast (Arun *et al.*, 2019; Shalini *et al.,* 2019). Many studies also exist in the Kerala coast as well (Aswathanarayana,1964; Prabhakara Rao,1968; Mallik, 1986; Purandara *et al.,*1987; Unnikrishnan,1987; Sasidharan and Damodaran,1988; Purandara,1990).

The coastal lands of Kerala are gifted with many placer mineral deposits having wide range of applications in the modern world. Black sands (ilmenite-rich heavy mineral placers), white sands (silica-rich sands) and construction grade alluvial sands are the common resources in the coastal lowlands. Among these the white sands or the silica-rich sands are the least studied resources in the coastal area, despite its industrial applications and geoenvironmental potential. The silica sand deposits of Kerala are distributed essentially in three locations: 1) Cherthala-Alappuzha;

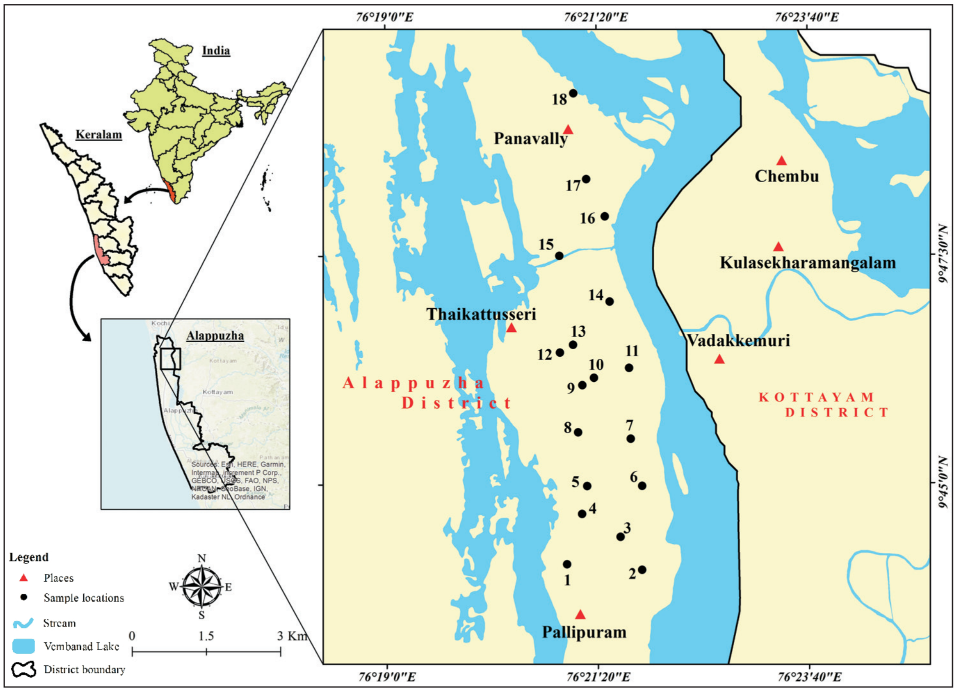

Fig. 1. Location map of the study area showing sampling locations

2) Kothamangalam and 3) Pallippuram-Panavally areas. The narrow coastal strip between Vembanad Lake and the Arabian Sea, which stretches roughly 35 kilometers from Cherthala to Arookutti, contains Kerala's most economically significant silica sand deposits. Around five meters above Mean Sea Level (MSL), these deposits are found as extensive sandy terrains that are often flat to gently sloping. Additionally, smaller patchy outcrops occur throughout the other districts in the state.

A preliminary review reveals that, although studies are available on the reserve estimates at certain localities and also bulk chemical composition, investigations on their origin, occurrence and mineralogical and geochemical composition of the silica sand resources of Alappuzha-Cherthala belt is scarce (Raghavan *et al.*, 2017). Therefore, an effort has been made in this study to examine the mineralogy and texture of the silica sand deposits of Alappuzha-Cherthala belt of Kerala coast to shed light on their textural maturity and mineralogical provenance.

Study Area and Geological Setting

Silica sands, also known as glass sands or white sands, are found in the Alappuzha district between Alappuzha (9°28'20"N, 76°20'E) and Cherthala (9°41'N, 76°20'E). Their abundance is noticed in the Panavally (9°48'N, 76°21'E) area of Alappuzha district (Fig. 1). This deposit runs along the western margin of the Vembanad Lake in almost a straight line for about 35 km. The Alappuzha district is situated in the southern part of Kerala State, encompassing an area of 1414 km^2. It is the smallest district in the state and constitutes only about 3.64% of its total area. The study area (Fig. 1) mainly comprised by unconsolidated sediments of Quaternary age which is underlined by semi-consolidated Neogene sediments of Warkalli, Quilon, and Vaikom Formations (Anooja *et al.,*2013; Padmalal *et al.,* 2025) as depicted in the Geology map (Fig. 2). Laterite is seen overlying the Tertiary (Neogene) and crystalline formations in the southeastern parts of Alappuzha district. Sedimentary formations cover approximately 83% of the district's geographical area. The Alappuzha district is recognized for its coastal alluvium, which is widely dispersed along the shoreline and is mainly made up of sand and clay. Residual lateritic formation is found in the southeastern part of the district. Occurrences of granitic rocks are reported in areas around Chengannur (Department of Mining and Geology, 2016).

Materials and Methods

Field Investigation and Sampling

A detailed field investigation was conducted in the study area to collect silica sand samples, and the sample locations are depicted in Fig. 1. The silica sand samples were collected at consistent intervals of 1 km from Pallippuram to Panavally and subjected to sedimentological and heavy mineral analysis. Field photographs of the study area are displayed in figure 3(a-c). In total, 18 surface and subsurface samples were collected for the present study. Subsurface samples were collected by penetrating a PVC pipe. All samples were examined for textural and mineralogical parameters to decipher the mineral distribution and sediment characteristics of the samples in the area.

Grain Size Characteristics

Following the method described by Carver (1971), representative subsamples were taken and it is then mechanically sieved using a Ro-Tap shaker at ½ ϕ intervals. The particle-size parameters were determined by the graphic method from cumulative weight percentages plotted on probability curves (Inman, 1952). These values were used to determine various grain size parameters. By using probability chart, the cumulative weight percentages of the samples were plotted against the corresponding grain sizes, expressed in phi (ϕ) units. Based on the methodology

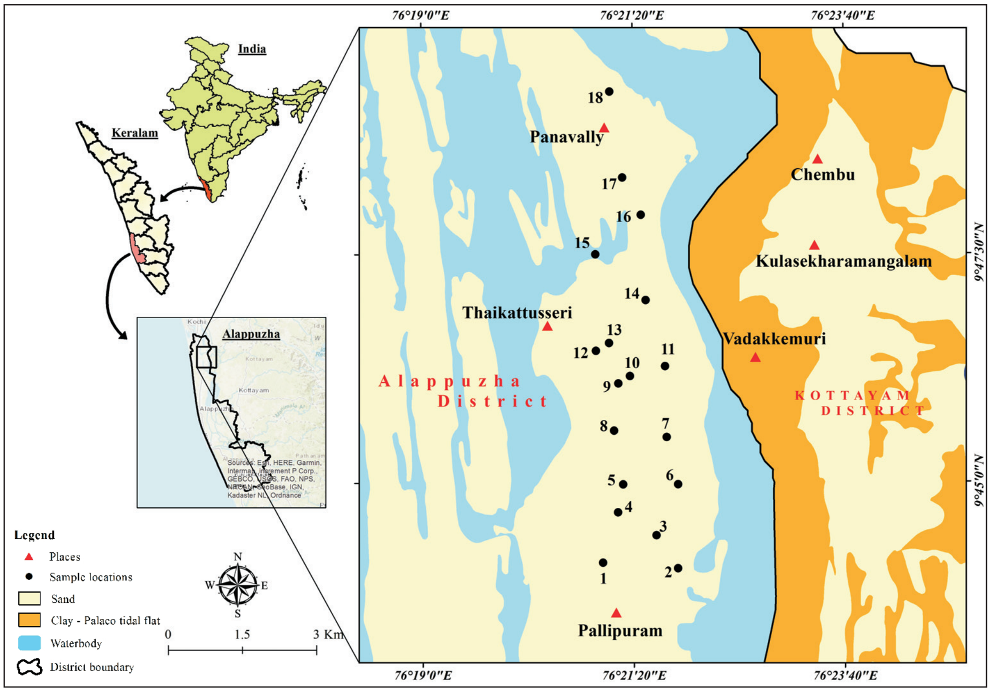

Fig. 2. Geological map of the study area

proposed by Folk and Ward (1957), statistical parameters such as the mean, median, standard deviation, skewness, and kurtosis were computed. As summarized in Table 1, the classification scheme and boundary values used in this analysis adhere to the generally recognized framework created by Folk and Ward (1957).

Table 1: The divisional limits of statistical parameters as suggested by Folk and Ward (1957)

Statistical parameter	Limits (Φ)	Class / terminology
a) Mean	<-8	Boulder
	-8 to -6	Cobble
	-6 to -5	Coarse Gravel
	-5 to -4	Medium Gravel
	-4 to -3	Fine Gravel
	-3 to -2	Very Coarse Sand
	-2 to -1	Coarse Sand
	-1 to 0	Medium Sand
	0 to 1	Fine Sand
	1 to 2	Very Fine Sand
	2 to 4	Silt
	4 to 8	Clay
	>8	Clay (very fine)
b) Standard Deviation	<0.35	Very Well Sorted
	0.35 to 0.50	Well Sorted
	0.50 to 0.71	Moderately Well Sorted
	0.71 to 1.00	Moderately Sorted
	1.00 to 2.00	Poorly Sorted
	2.00 to 4.00	Very Poorly Sorted
	>4.00	Extremely Poorly Sorted
c) Skewness	>0.30	Strongly Fine Skewed
	0.30 to 0.10	Finely Skewed
	0.10 to -0.10	Symmetrical
	-0.10 to -0.30	Coarse Skewed
	<-0.30	Strongly Coarse Skewed
d) Kurtosis	<0.67	Very Platykurtic
	0.67 to 0.90	Platykurtic
	0.90 to 1.11	Mesokurtic
	1.11 to 1.50	Leptokurtic
	1.50 to 3.00	Very Leptokurtic
	> 3.00	Extremely Leptokurtic

Fig.3. Field photographs showing **a)** A distant view of Silica sand dune deposits of Cherthala; **b)** Vertical section of the silica sand deposit; **c)** Silica sample collected for analysis

Geostatistics

Mean Size

The mean, a statistical average denoted in phi (ϕ) units which is assessed using the following formula:

$$\text{Mean Size (Mz)} = \frac{\phi 16 + \phi 50 + \phi 84}{3} \quad (1)$$

Standard Deviation

The standard deviation evaluates the sorting of grains that constitute a sediment population. The uniformity of a sediment sample is quantified by this standard deviation. It is considered as the most beneficial criteria for diagnosing the sorting efficiency of the depositional medium.

$$\text{Standard deviation } (\sigma) = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \quad (2)$$

Skewness

Skewness measures the asymmetry of the particle-size distribution in a sediment sample. The skewness index proposed by Folk and Ward (1957) is the ideal method because it considers the entire curve.

$$\text{Skewness (Sk)} = \frac{\phi 84 + \phi 16 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 95 + \phi 5 - 2\phi 50}{2(\phi 95 - \phi 5)} \quad (3)$$

Kurtosis

Kurtosis is a major textural parameter for differentiating several deposition environments (Mason and Folk, 1958). It is a degree of the amount of disparity between the sorting perceived in the central part of the grain size distribution and the tails.

$$\text{Kurtosis (Kg)} = \frac{\phi 95 - \phi 5}{244\,(\phi 75 - \phi 25)} \quad (4)$$

SEM Analysis

Scanning Electron Microscopy is an important tool for examining the micro morphological characteristics of minerals and their modification aspects. These investigations are crucial for understanding the processes of weathering, transportation, and succeeding changes in depositional environments (Krinsley and Doomkamp, 1973). The SEM analysis was conducted following the standard protocols recommended by Goudie and Bull (1984). The photomicrographs were interpreted according to the methods described by Georgieva and Stoffers (1980) and Marshall (1987).

Heavy Mineral Analysis

The sand fractions were washed, oven-dried (50 ± 3 °C), and condensed by coning and quartering (~100 g). The mixture was then sieved using a Ro-tap shaker. Heavy and light minerals (+45 to +230 mesh) were separated using bromoform, cleaned, dried, and then weighed. Heavy residues were acid-treated, mounted with Canada balsam, and identified using a Leitz petrological microscope following standard petrographic methods.

Results

Granulometric Analysis

Table 2 provide a summary of the differences in textural grades across the silica sand samples in the study area. The particle sizes in the surface samples ranged from coarse to fine sand. The surface sediments contain a significant amount of fine sand, with its concentration ranging from 11.2% to 57.3%. The subsurface samples were predominantly composed of fine sand. The fine sand composition ranged from 25.66% to 66.50%, with an average of 41.06%. The range of medium sand content was from 19.77% to 42.09% (average 31.56%).

In the Alappuzha-Cherthala belt, the quantities of very fine and very coarse sand are marginal. Fig. 4.a-b shows the distribution of different size grades of the samples in surface and subsurface silica sand deposit of the Alappuzha - Cherthala belt. Samples were collected from the northern, central, and southern sectors of the deposit. Fig. 5 shows the average values of different size fractions within the surface and subsurface sediments of the study area.

Table 2: Textural grades of sand fraction in the surface and subsurface sediments of the study area

Sample number	Location name	Surface Sediments (Size percentage)					Subsurface Sediments (Size percentage)				
		Very coarse	Coarse	Medium	Fine	Very fine	Very coarse	Coarse	Medium	Fine	Very fine
1	Ottappunna	2.426	17.5	56.9	20.2	2.85	1.18	13.72	32.54	47.55	5.00
2	Pallippuram	0.994	20.86	38.34	36.7	3.04	1.7	22.0	36.25	36.51	3.50
3	Pallippuram (Near Church)	1.321	20.5	35.5	39.4	3.23	1.13	14.99	35.05	44.98	3.82
4	Kelamangalam	4.205	47.4	27.7	19.3	1.2	6.3	39.83	23.25	28.22	2.35
5	Valluvel	2.177	31.5	25.2	36.5	4.5	1.2	5.501	19.77	66.5	6.96
6	Vellimittam	0.541	14.4	32.3	48.5	4.11	1.41	29.86	36.28	30.38	2.04
7	Punnakkal	1.102	17.9	33.4	43.4	4.04	2.02	29.59	29.78	36.18	2.41
8	Kadambana Kulangara	1.506	16.7	31.8	44.7	5.1	1.7	16.84	39.84	37.62	3.94
9	Ayyappikkunnu	1.315	20.8	35.4	38.6	3.7	1.1	32.29	34.37	30.34	1.86
10	Koppazha	1.704	18.3	67.1	11.2	2.5	0.55	26.03	40.92	30.65	1.82
11	Makkekadal	0.362	8.5	26.15	57.3	7.6	0.8	7.12	25.79	61.03	5.25
12	Cheerathukadu	1.642	30.4	26.3	39.2	2.3	2.6	42.34	23.84	29.36	1.82
13	Adua	0.544	14.6	27.2	51.4	6.1	1.01	15.07	26.94	50.33	6.63
14	Varekkad	3.77	21.9	27.2	42.9	4.1	1.7	2.77	27.6	55.09	4.52
15	Kalathil Junction	0.466	27.2	37.7	32.1	2.4	0.55	17.71	28.8	48.66	4.18
16	Poochakkal	0.759	18.8	27.03	46.8	6.5	0.7	23.88	42.09	30.91	2.35
17	Odampalli	1.101	10.9	34.06	49.1	4.7	1.2	13.22	30.18	49.07	6.24
18	Padmapuram	1.05	32.1	44.35	20.3	2.3	0.4	37.91	34.80	25.66	1.17

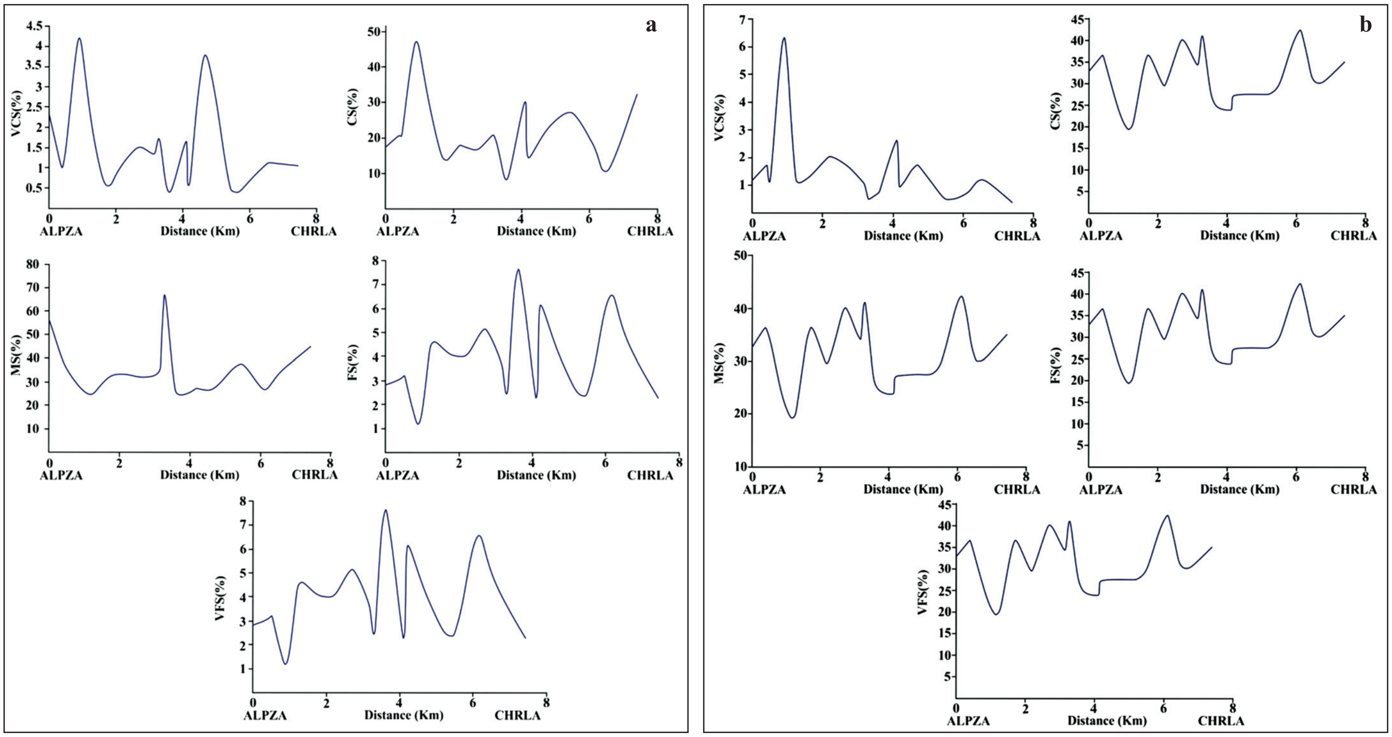

Fig. 4a. Spatial variations of size fractions in the **a)** surface sediments; **b)** subsurface sediments of the study area from Alappuzha (ALPZA) to Cherthala (CHRLA)

Statistical Analysis

Mean Size Study

In the study area, the average size of the surface sediments ranged from 1.3 to 2.21 ϕ, with an average of 1.75 ϕ (Table 3). The sample obtained from Koppazha (Sample No. 10) exhibited the smallest average size, whereas the sample obtained from Makkekadal (Sample No. 11) had the largest average size. The mean size data of the surface samples indicate that the transportation agent is of moderate size (Folk and Ward, 1957). An examination of the average size indicated that 83.33% of the samples consisted of medium sand, while the remaining 16.66% consisted of fine sand. The study of surface samples indicated that Makkekadal, Odampalli, and Kelamangalam contained fine sand, whereas the other samples consisted of medium sand. The average size of the subsurface sample ranged from 1.38 to 2.23 ϕ, with an average value of 1.8 ϕ (Table 3). The subsurface sample obtained from Cheerathukadu recorded the highest average size, whereas the sample from Kadambana Kulangara recorded the lowest average size value. Of all the particles, 77.7% were classified as medium sand, whereas 22.2% were classified as fine sand. Samples from Makkekadal, Valluvel, and Kadambana Kulangara belonged to the fine sand category, whereas all other samples belonged to the medium sand category.

Standard Deviation Study

The results of the standard deviation in the surface samples collected from the Alappuzha-Cherthala belt are presented in Table 3. The lowest value of 0.58 ϕ was observed in the Odampalli sample (Sample No. 17), while the highest value of 0.91 ϕ was found in the Varekkad Sample No (Sample No. 14). The average standard deviation of the surface samples was 0.75 ϕ. The data analysis indicated that 77.7% of the sediments exhibited a moderate level of sorting, while 22.2% were categorized as moderately well sorted. For subsurface samples, the sorting value varied between 0.57 and 0.92 ϕ, with an average of 0.74 ϕ (Table 3). Of the subsurface samples, 66.6% of the sediments were moderately sorted, whereas 33.3% were moderately well sorted. The sorting values in these samples varies from moderately to fairly well sorted.

Skewness Study

Tables 3 provide skewness values for the surface and subsurface samples in the study area. The samples have a

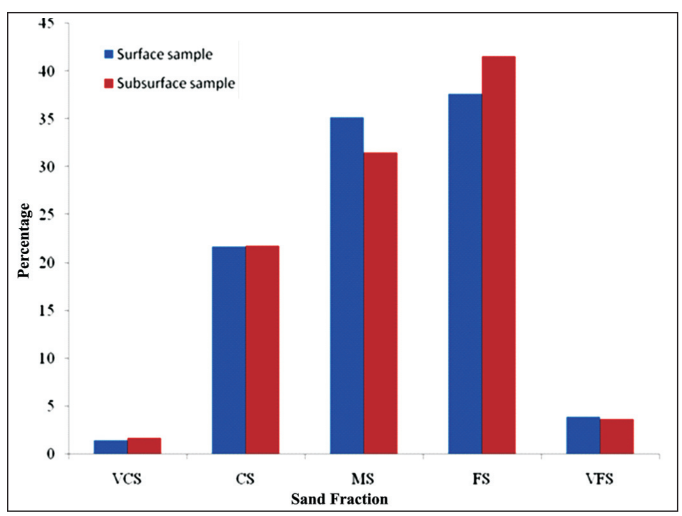

Fig. 5. Average values of different size fractions within the surface and subsurface sediments of the study area.

Table 3: Statistical parameters of surface and subsurface samples in the Alappuzha - Cherthala belt

Sample No.	Location	Surface				Subsurface			
		Mean	Standard Deviation	Skewness	Kurtosis	Mean (Φ)	Standard Deviation (Φ)	Skewness	Kurtosis
1	Ottappunna	1.4 (medium sand)	0.75 (moderately well sorted)	-0.12 (coarse skewed)	1.229 (leptokurtic)	1.95 (medium sand)	0.723 (moderately well sorted)	-0.1 (coarse skewed)	1.178 (leptokurtic)
2	Pallippuram	1.733 (medium sand)	(0.728) moderately well sorted	-0.168 (coarse skewed)	1.15 (leptokurtic)	1.716 (medium sand)	0.776 (moderately sorted	-0.24 (coarse skewed)	0.983 (mesokurtic)
3	Pallippuram (Near Church)	1.766 (medium sand)	0.76 (moderately sorted)	-0.208 (coarse skewed)	1.03 (mesokurtic)	1.8 (medium sand)	0.723 (moderately sorted)	-0.27 (coarse skewed)	0.992 (mesokurtic)
4	Kelamangalam	2.08 (fine sand)	0.63 (moderately sorted)	-0.15 (coarse skewed)	1.43 (leptokurtic)	1.416 (medium sand)	0.926 (moderately sorted)	-0.115 (coarse skewed)	0.935 (mesokurtic)
5	Valluvel	1.6 (medium sand)	0.81 (moderately sorted)	-0.29 (coarse skewed)	0.71 (platykurtic)	2.3 (fine sand)	0.598 (moderately well sorted)	-0.295 (coarse skewed)	2.28 (very leptokurtic)
6	Vellimittam	1.9 (medium sand)	0.75 (moderately sorted)	-0.19 (coarse skewed)	1.27 (leptokurtic)	1.65 (medium sand)	0.748 (moderately sorted)	-0.137 (coarse skewed)	0.725 (platykurtic)
7	Punnakkal	1.83 (medium sand)	0.75 (moderately sorted)	-0.25 (coarse skewed)	1.2 (leptokurtic)	1.65 (medium sand)	0.836 (moderately sorted)	-0.205 (coarse skewed)	0.761 (platykurtic)
8	Kadambana Kulangara	1.88 (medium sand)	0.78 (moderately sorted)	-0.17 (coarse skewed)	1.18 (leptokurtic)	2.23 (fine sand)	0.728 (moderately sorted)	-0.231 (coarse skewed)	1.25 (leptokurtic)
9	Ayyappikkunnu	1.76 (medium sand)	0.74 (moderately sorted)	-0.19 (coarse skewed)	1.17 (leptokurtic)	1.616 (medium sand)	0.817 (moderately sorted)	-0.091 (nearly symmetrical)	0.737 (platykurtic)
10	Koppazha	1.3 (medium sand)	0.607 (moderately sorted)	-0.22 (coarse skewed)	1.14 (leptokurtic)	1.64 (medium sand)	0.654 (moderately well sorted)	-0.183 (coarse skewed)	0.753 (platykurtic)
11	Makkekadal	2.21 (fine sand)	0.68 (moderately sorted)	-0.06 (coarse skewed)	1.22 (leptokurtic)	2.13 (fine sand)	0.573 (moderately well sorted)	-0.133 (coarse skewed)	1.292 (leptokurtic)
12	Cheerathukadu	1.68 (medium sand)	0.82 (moderately sorted)	-0.258 (coarse skewed)	0.708 (platykurtic)	1.375 (medium sand)	0.758 (moderately sorted)	-0.259 (coarse skewed)	1.821 (leptokurtic)
13	Adua	1.95 (medium sand)	0.81 (moderately sorted)	-0.208 (coarse skewed)	0.68 (platykurtic)	1.9 (medium sand)	0.758 (moderately sorted)	-0.247 (coarse skewed)	1.024 (leptokurtic)
14	Varekkad	1.75 (medium sand)	0.91 (moderately sorted)	-0.35 (coarse skewed)	0.823 (platykurtic)	2.083 (fine sand)	0.643 (moderately well sorted)	-0.160 (coarse skewed)	1.284 (leptokurtic)
15	Kalathil Junction	1.66 (medium sand)	0.72 (moderately sorted)	-0.08 (coarse skewed)	0.46 (very (platykurtic)	1.883 (medium sand)	0.720 (moderately sorted)	-0.251 (coarse skewed)	1.092 (leptokurtic)
16	Poochakkal	1.9 (medium sand)	0.843 (moderately sorted)	-0.24 (coarse skewed)	1.06 (mesokurtic)	1.666 (medium sand)	0.708 (moderately sorted)	-0.156 (coarse skewed)	0.784 (platykurtic)
17	Odampalli	2.08 (fine sand)	0.58 (moderately sorted)	-0.12 (coarse skewed)	1.35 (leptokurtic)	1.9 (medium sand)	0.698 (moderately well sorted)	-0.272 (coarse skewed)	0.725 (platykurtic)
18	Padmapuram	1.51 (medium sand)	0.67 (moderately sorted)	-0.32 (coarse skewed)	1.106 (leptokurtic)	1.533 (medium sand)	0.673 (moderately well sorted)	-0.02 (nearly symmetrical)	0.763 (platykurtic)

distribution with a tail of fines for positive values of skewness, whereas negative values of skewness imply a distribution with a tail of coarseness. Surface samples had skewness values varies from -0.35 to -0.06, with an overall average of -0.20. All surface samples fell into the category of coarse skewed. The sample gathered from Varekkad exhibited the lowest skewness, whereas the sample from Makkekadal displayed the highest skewness. The subsurface samples exhibited a range of -0.27 to -0.02 (average -0.15). Of all the subsurface samples, 88.8% exhibited a coarse skewed distribution, whereas 11.1% displayed a nearly symmetrical distribution. The samples from Padmapuram and Ayyappikkunnu exhibited almost symmetrical skewness. The skewness values of the sediment samples exhibited minor variability throughout the vertical profile and tended to be skewed towards near symmetry. The negative skewness of the sands indicates that they originated from a beach environment. Although the sand is slightly shaped into foredunes, its genetic characteristics remain well-preserved in the sediment population.

Kurtosis Study

The kurtosis values of the surface samples ranged from 0.46 to 1.43, with an average value of 0.95. The samples revealed a range of kurtosis, from platykurtic to leptokurtic. The majority of the sample exhibits leptokurtic behaviour. The sample collected from Kalathil Junction exhibited the lowest kurtosis value, whereas the Kelamangalam sample demonstrated the highest kurtosis value. The analysis of the entire set of surface samples indicated that 5.5% of the samples exhibited a high degree of flatness, 22.2% were moderately flat, 11.1% had a normal level of flatness, and 61.1% were highly peaked (Table 3). The mean kurtosis of the subsurface samples was 1.5, with a range of 0.72–2.28. The sample taken from Odampalli exhibited the lowest kurtosis value, whereas the sample collected from Valluvel exhibited the highest kurtosis value. Of the given samples, 11.1% exhibited a high degree of peakedness, 22.2% exhibited a moderate degree of peakedness, 27.7% exhibited an average degree of peakedness, and 38.8% exhibited a low degree of peakedness.

Bivariate Plots

Bivariate plots were worked out to understand the interrelationships among the statistical parameters. Bivariate plots between the values of the standard deviation, mean, skewness, and kurtosis (Fig. 6a-b) were drawn to comprehend the nature of the distribution of different size parameters calculated from the samples (Sivasamandy and Ramesh, 2014).

CM Pattern

To understand the mode of sediment transportation, the CM pattern was determined using the highest 1 percentile, C, against the average size, M, of the samples (Passega, 1964; Murkute, 2001). The overall pattern of the diagram has segments NO, OP, PQ, QR, and RS, each revealing a specific mode of transportation. Figures 7.a-b shows the CM diagram of the samples from the study region. Alappuzha-Cherthala surface samples showed a noticeable clustering of points within the OP segments in the CM pattern. This implies that the sediments were moved by rolling and suspension in the environment.

SEM Observations and Environmental Discriminations

The SEM images of a few quartz grains collected from the Pallippuram area are shown in figure 8. The grains are presented at magnifications ranging from 160× to 300×, relative to their original size. The rounded to sub-rounded nature of the grains exhibit various surface textural features. Bulbous edges, linear grooves, solution pits, and ridges are common on the grain surface. The surface textural features indicate the maturity of the grains before deposition at the present site as a silica sand deposit. The grains have undergone long-distance transportation in a high-energy environment, presumably a beach/nearshore environment.

Heavy Minerals

Heavy minerals are found in accessory amounts in siliciclastic sediments (Fig. 8) and rocks; however, even its small amounts in the samples, they provide valuable data about source rocks, environmental circumstances, and transportation processes (Dunkl *et al.*, 2020). A petrological microscope was used to identify the heavy minerals under polarised light. The presence and

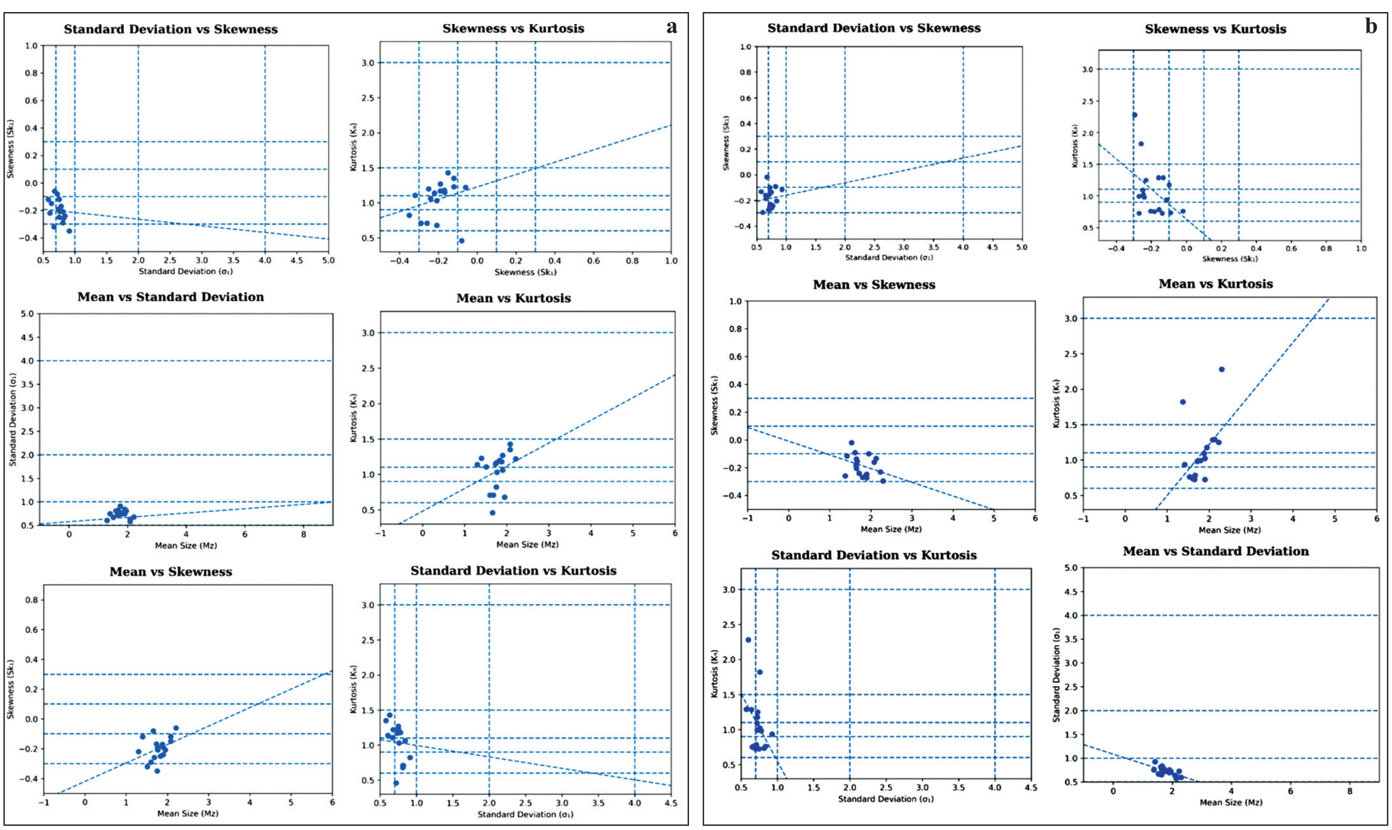

Fig. 6. Bivariate plots of **a.** surface samples **b.** subsurface samples in the study area.

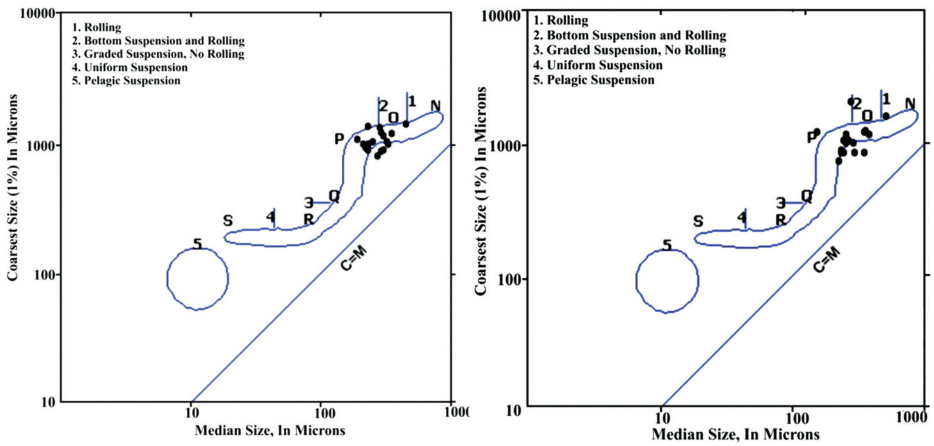

Fig. 7. CM pattern worked out for **a.** surface **b.** subsurface samples in the study area

distribution of heavy elements in sediments can provide insights into the characteristics of the original rock source and the conditions under which the sediments evolved (Milner., 1962; Flores and Shideler, 1978). Ilmenite, sillimanite, zircon, monazite, rutile, garnet, and other similar minerals were commonly discovered in sediments as heavy minerals (Fig. 9). Table 4 displays the outcomes of the heavy mineral analysis carried out in the samples of the study region. The dominant minerals in the heavy mineral suite included opaques, sillimanite, zircon, rutile, garnet, and pyribole (a combination of pyroxene and amphibole). The heavy mineral concentration in the fine sands of the Cherthala surface sand ranged from 0.71% to 5.72%, with an average of 2.71%, whereas the light mineral percentage in the region ranged from 94.28% to 99.25% (average 97.24%). Sample No. Sample 16 (Poochakkal) had the lowest concentration of Total Heavy Minerals (THM), whereas Sample No. 2 (Pallippuram) had the highest concentration. Figure 10 illustrates the changes in the overall content of dense minerals in the surface sediments across the north-south direction in the Alappuzha-Cherthala region. In the heavy mineral assemblage, sillimanite and opaque minerals occur in major amounts, whereas other minerals occur in minor or trace amounts. The spatial variations of the sillimanite (a typical lighter heavy mineral) and opaques (heavier heavy mineral) show an antipathetic relationship, which may be attributed to the differences in the hydrodynamic behavior of these grains. The lighter heavies will be transported in higher proportions while the heavier heavies will remain in the

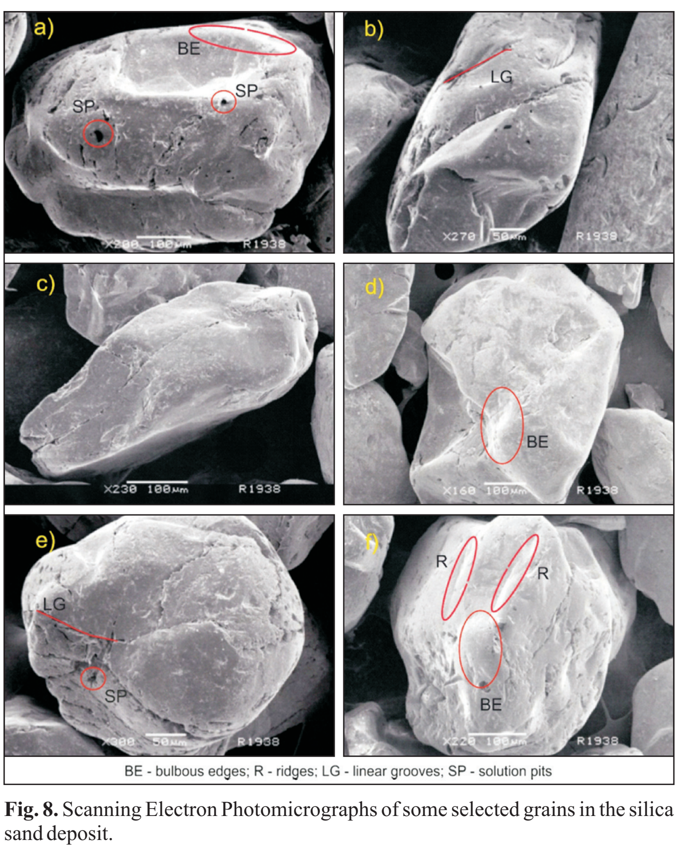

Fig. 8. Scanning Electron Photomicrographs of some selected grains in the silica sand deposit.

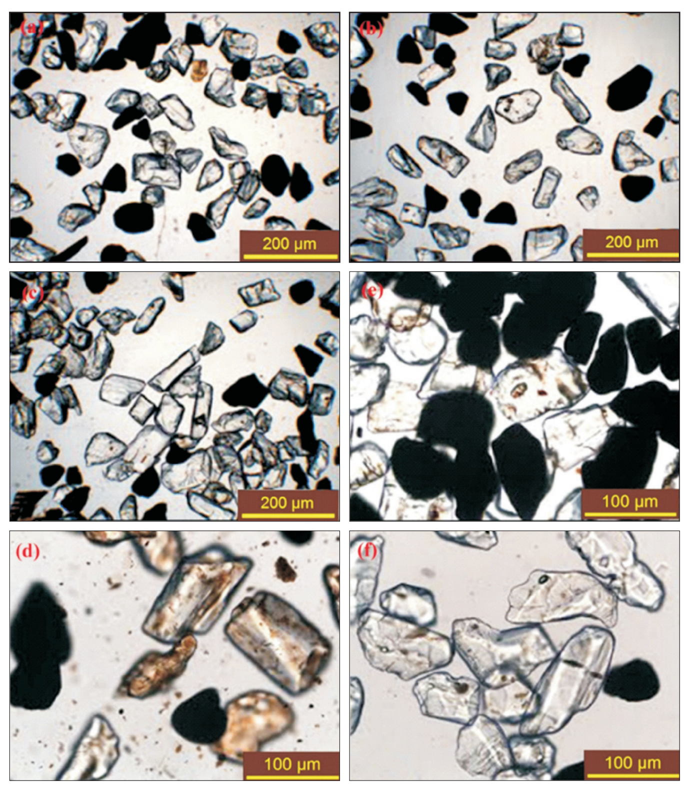

Fig. 9. Photomicrographs of heavy minerals in silica sand deposits: **(a - c)** heavy mineral assemblage under low magnification, **(d - f)** heavy mineral assemblage under high magnification. In high magnification photomicrographs the dark-coloured opaque minerals are mainly ilmenite and the light elongated transparent minerals are sillimanite.

Table 4: Heavy mineral concentration in the study area

Sample	THM (Wt %)	TLM (Wt %)	Non-MF (number%) in 100%						
			Opaques	Sillimanite	Zircon	Rutile	Garnet	Pyribole	Others
CS-1	3.31	96.69	36.60	60.38	0.75	0.38	-	0.75	1.13
CS-2	5.72	94.28	53.42	44.38	0.55	0.27	0.27	-	1.10
CS-3	3.44	96.56	28.41	68.94	0.76	-	-	0.76	1.14
CS-4	1.68	98.32	24.03	72.87	0.78	-	-	-	2.33
CS-5	1.36	98.64	13.75	83.75	1.25	-	-	-	1.25
CS-6	2.96	97.04	21.67	75.67	1.67	-	-	-	1
CS-7	2.86	97.14	35.84	61.75	0.90	-	0.60	-	0.90
CS-8	2.19	97.81	22.77	74.26	0.99	0.50	0.50	-	0.99
CS-9	3.93	96.07	34.38	63.67	0.78	-	0.39	-	0.78
CS-10	3.16	96.84	30.36	67.41	1.34	-	-	-	0.89
CS-11	4.04	95.96	13.83	84.44	0.58	-	0.29	-	0.86
CS-12	1.16	98.84	13.68	83.02	2.36	-	-	-	0.94
CS-13	1.55	98.45	17.65	79.21	1.96	-	-	-	1.18
CS-14	0.75	99.25	6.86	90.20	0.98	-	-	-	1.96
CS-15	2.77	97.23	27.82	69.17	1.88	-	-	-	1.13
CS-16	0.71	98.29	13.03	85.64	0.80	-	-	-	0.53
CS-17	2.35	97.65	22.92	75.09	0.99	-	-	-	0.99
CS-18	3.85	96.15	31.64	64.84	0.78	0.39	-	1.17	1.17

sample sites as lag concentrates during the aeolian activity. This may be due to observed spatial variability.

Opaques

Opaque minerals were present in all inspected samples. Hematite, magnetite, and ilmenite constitute opaque materials. The most abundant opaque mineral in heavy mineral content is ilmenite. The proportion of opaque minerals in the fine sand fractions of the study area ranged from 6.86% to 53.42%, with an average of 25.45%. The highest concentration (53.42%) was observed in Sample No.1 and the lowest (6.86%) in Sample No. 7. Figure 10 shows the longitudinal distribution of opaque materials in the surface sediments of the study area.

Sillimanite

All surface sediment samples contained significant concentrations of sillimanite. The heavy mineral residue is distinguished by a greater proportion of sillimanite compared to opaque minerals. The predominant minerals in the heavy mineral suite were opaque and sillimanite. In the investigated region, the average amount of sillimanite in the fine sand fraction of the sediments was 71.96%, with a range of 44.38% to 90.20%. Sample 14 exhibited the highest concentration of sillimanite at 90.20%, whereas Sample 2 had the lowest concentration at 44.38%.

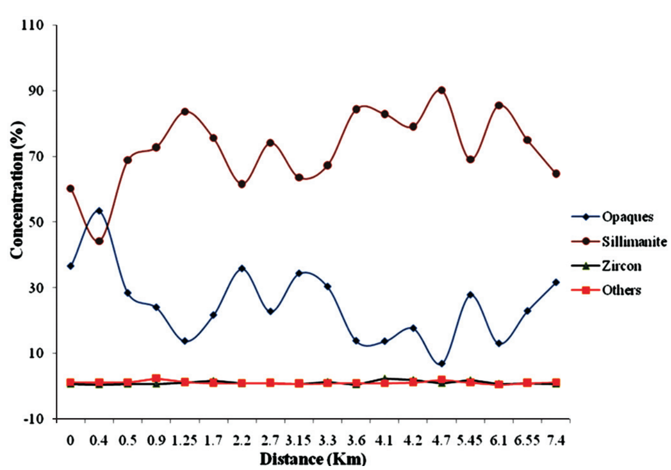

Fig. 10. Spatial variation of heavy mineral concentration in the study area.

Zircon

The mean zircon concentrations in the finer sand fractions of the study region were 1.15% (range: 0.55%–2.36%). Zircon is widely regarded as an important indicator mineral in numerous petrographic investigations. The mineralogical properties of zircon provide valuable information on the physical and chemical conditions under which it was formed.

Minerals in Trace Amounts

The heavy mineral assemblage contains trace amounts of garnet, pyribole (pyroxene + amphibole), and rutile. A limited number of samples in the study area contained these trace minerals. The rutile content in the study area varied between 0.27% and 0.5%, with an average of 0.39%. In this study, minerals that have undergone significant alteration or cannot be identified using standard mineral specimens are categorized as 'other minerals.' The mean concentrations of garnet and pyribole were 0.42% (0.27%-0.6%) and 0.92% (0.75%-1.17%), respectively.

Discussion

Although a very important resource of the modern era, silica-sand deposits have been studied the least. An attempt has been made in the present study using granulometric analysis to interpret the sedimentary environment and mechanism of transportation and deposition of the silica sand deposits of Alappuzha-Cherthala belt in Kerala. Figure 6a-b reveals that the silica sand in the area was deposited under fluctuating energy conditions. The well-rounded nature of the sand grains indicates that the sediment particles were transported far away from their original source area. The size of the silica sands varies between very coarse sand (0.4-6.3 ϕ) and very fine sand (1.17-6.96 ϕ), with medium-sized grains predominant, especially in the Pallippuram, Ottappunna, Padmapuram, Kelamangalam, Kalathil junction, and Koppazha areas.

The skewness values of the sediment samples exhibited minor variability throughout the vertical profile and tended to be skewed towards symmetry. Surface samples and the majority of the subsurface samples exhibited a coarse skewed distribution, whereas approximately 11% of the subsurface samples displayed a nearly symmetrical distribution. Sorting, a gauge of the range of grain sizes, typically manifests energy levels in the depositional environment and the permanence of conditions with that energy level with time. The surface and subsurface sands were moderately to well sorted. The kurtosis value of the surface samples ranged between 0.46 and 1.43, with an average kurtosis value of 0.95. Majority of samples displayed leptokurtic behaviour. According to Friedman (1962), extremely high or low kurtosis values imply that at least a part of the sediment attained its sorting in a high-energy environment. Folk and Ward (1957) proposed that beach sediments may display utmost kurtosis values because of well sorting imparted by a high-energy environment. The leptokurtic behavior of the present samples indicates sediment sorting in a high-energy environment but later redeposited at the present site by aeolian activity.

The bivariate plot of the graphic mean versus the graphic standard deviation (Fig. 6a-b) indicates that the silica sand samples fall within the beach environment (Friedman, 1961; Moiola and Weiser, 1968). Bivariate plots of the samples collected from the beach and dune environments fell within the same type of deposition environment. The roundness and sphericity values of the silica sand point towards reworking in a fluvial regime and short-distance transportation (Pettijohn *et al.*, 1972; Van Hateren *et al.,* 2020).

The foregoing discussions on textural analysis reveal that in the study area, the sediment distribution is influenced by a wave-dominated regime. CM pattern (Fig. 7a-b) shows that the sediments are primarily deposited as rolling and graded suspension through wave activity. The general unimodal nature of the sediment distribution signifies a dominant single-source rock (Blatt *et al.*, 1972). Scatter plots of grain size parameters were outlined to better comprehend the depositional environments and processes of sediment transportation. The trend shown by the bivariate plot of mean grain size against sorting is that sorting improves as grain size decreases. The almost symmetrical skewness and low standard deviation values indicate that most surface sediment samples are moderately sorted, reflecting a relatively uniform grain-size distribution. The reworked nature of the sediments and the influence of high-energy wave action probably caused the coarser fractions to be selectively removed, resulting in finer, better-sorted deposits. Platykurtic to mesokurtic distributions, which show a balanced representation of several grain size modes, also developed as a result of the concentration of grain sizes within a small range. According to Reddy *et al.* (2008), the introduction of coarser particles carried by longshore currents may be the cause of the slight negative skewness observed in some samples. The ongoing high-energy hydrodynamic conditions in the study region appear to facilitate the removal of coarse, low-density minerals, thereby increasing the comparative enrichment of heavy minerals in finer grain size classes.

The major heavy mineral components present in the study area are opaques, sillimanite, zircon, magnetite, rutile, garnet etc. The heavy mineral assemblages demonstrated a low overall concentration (*avg.* 2.71% THM) with a dominance of sillimanite and opaque minerals, indicating a predominantly high-grade metamorphic source. Spatial variation and the adverse relationship among sillimanite and opaques reflect density-controlled hydrodynamic sorting, with heavier minerals forming lag concentrates. Ilmenite-rich opaques suggest localized placer enrichment, whereas the presence of zircon, rutile, and garnet indicates a mixed and possibly recycled provenance. Overall, the sediments exhibited moderate mineralogical maturity, influenced by coastal and aeolian processes.

The present study revealed that longshore currents play an important role in sorting heavy and light mineral fractions in coastal sediments along the Kerala coast in southwest India (Babu and Thrivikramji, 1993). The increase in the heavy mineral content in the fine and very fine sand fractions can be accredited to the selective entrainment and transport of heavy minerals by coastal currents (Komar and Wang, 1984).

The heavy mineral distribution in Cherthala implies a sialic igneous and metamorphic origin for the silica sand (Kumar and Sreejith, 2016). Monazite, zircon, and rutile are generally found in sialic igneous rocks such as granite and pegmatites, while sillimanite implies a metamorphic origin (Carver, 1971; Lewis and McConchie, 1994). The heavy minerals not only endure density-based sorting processes, but also undergo size-based sorting as well; thus, tending to be concentrated in the finer size portions (Komar and Wang, 1984; Peterson *et al.,* 1986). It is observed that comparatively low dense components (*e.g.,* sillimanite) are transported farther northward by longshore currents than high dense heavy minerals (*e.g.,* opaques, monazite etc.). This finding was reiterated by Anooja *et al.* (2013), who stated that the longshore drift caused the transportation of sediments derived from the garnet-sillimanite gneisses province in the hinterland area south of the Achankovil Shear Zone (*i.e.,* the Trivandrum block).

Regional geology shows that the Western Ghats are mostly made up of charnockite and leptinites with acid igneous rocks such as granite and pegmatite intrusions (Kumar and Sreejith, 2016). Khondalite has more sillimanite, granite has more rutile and zircon, and pegmatites have more monazite than the other rock types in the area. Thus, the khondalite belts, granites, and pegmatites in the hinterlands of the Trivandrum Kollam coast could be the potential source area for the sediments in the Alappuzha - Cherthala coast. The middle to late Holocene transgression and aeolian activity in the subsequent aridity might have played a pivotal role in the formation of dunes and their observed heavy mineralogical diversity in the study area.

Conclusions

The Western Ghat region, located south of the Achankovil Shear Zone and comprising the Kerala Khondalite Belt (KKB), hosts rock groups enriched with mineral suites such as garnet, sillimanite, and other constituents of silica sand. These minerals, primarily derived from intense weathering processes, are transported by rivers to the coast and nearshore regions. Subsequently, longshore currents transported these sediments northward and deposited them along the beach fronts. The lighter mineral quartz and the lighter heavy fraction sillimanite continued to move further north through aeolian processes during the aridity period and developed as foredunes. The sands in the forefront of the Cherthala coastal belt exhibit a symmetrical to near-symmetrical grain population with rounded to subrounded shapes, a characteristic feature of aeolian deposition. In short, it was revealed that the denuded products from the hinterlands, especially the Trivandrum block, are subjected to size- and density-based sorting in the coastal near-shore environments. During the Early to Middle Holocene, these sediments moved northward and were later subjected to aeolian activity at the beginning of the Late Holocene, which is known as the aridity event in the region and globally. The observed textural and mineralogical investigations support this view.

Authors' Contributions

VS: Conceptualization, Methodology, Writing-Original draft Preparation, Supervision. **AP:** Data Curation, Reviewing and Editing, Visualization. **SVM:** Investigation**,** Reviewing and Editing. **PKAN:** Reviewing and Validation. **ARM:** Writing-Original Draft Preparation and Editing.

Conflict of Interests

The author(s) hereby declare that there is no conflict of interest regarding the publication of this research. The work presented is original, and no financial, personal, or professional relationships could inappropriately influence or bias the content of this study.

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