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Research Article

Textural characteristics of sediments and the distribution of heavy minerals in the coastal region between Sipasurabil and Bramhagiri, east coast of Odisha, India

R B Rao*[,a], B Mishra[b], S Rourtray[c], R Swain[d], S S Srikant[e] & D Singh[b]

[a]Formerly at CSIR - Institute of Minerals & Materials Technology, Bhubaneswar, Odisha – 751 012, India
[b]Formerly at IREL (India) Limited, Chhatrapur, Odisha – 761 020, India
[c]Centurion University of Technology and Management, Bhubaneswar, Odisha – 752 050, India
[d]C V Raman Global University, Bhubaneswar, Odisha – 752 054, India
[e]Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Delhi-NCR Campus, Modinagar, Ghaziabad, Uttar Pradesh – 201 204, India
*[E-mail: bhimaraoscientist1978@gmail.com]

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This study focuses on the textural characteristics of beach sand, specifically examining the lighter mineral group quartz, and the total heavy minerals in the coastal deposits from Sipasurubili to Brahmagiri in Odisha. The research area spans 3 kilometres along the coast and 1 kilometre in width. Samples were collected during three different seasons from the shoreline, backshore, frontal dune, central dune, and back dune. These samples were analysed using several statistical parameters, including graphical mean grain size, standard deviation, skewness, and kurtosis, to assess the sedimentary characteristics. Findings indicate that the graphical analysis of sediment grain sizes from Sipasurubili to the Brahmagiri coast, specifically from shore to back dune sand samples collected during autumn, summer, and winter, suggests that the graphical mean size for beach sand and quartz is nearly equivalent. In contrast, the observations regarding heavy minerals differ. The heavy minerals observed are ilmenite, rutile, sillimanite, garnet, zircon and monazite. Skewness analysis demonstrates that quartz particles exhibit a highly skewed distribution across all seasons of quartz and heavy mineral concentration. Furthermore, the particle distribution of heavy minerals shows similar skewness in both autumn and summer, in contrast to the distribution observed during the winter season across various concentration zones. It has been noted that quartz displays a mesokurtic distribution, while total heavy minerals exhibit both mesokurtic and platykurtic characteristics, particularly during the summer season.

[**Keywords**: Graphical mean size, Kurtosis, Sedimentary, Skewness, Sorting, Texture]

Introduction

Sipasurubili village is located in the Puri district of Odisha, covering a total geographical area of 15.47 square kilometres. The village falls under the jurisdiction of Brahmagiri, which serves as the sub-district headquarters and is situated 8 kilometres away. The district headquarters, Puri, is located 28 kilometres from Sipasurubili. The Mahanadi River system, along with its tributaries, including the Bhargavi and Bhargati rivers, plays a significant role in sedimentation and mineral concentration along the coastal stretch from Sipasurubili to Brahmagiri. The geological features and placer mineral deposits along the coastline from Sipasurubili to Brahmagiri form a long sandbar between Chilika Lake and the Bay of Bengal. This sandbar runs parallel to the shoreline and is positioned well above the high tide line. The area under study is marked by moderately developed frontal dunes that align with the coastline. Additionally, inter-dunes and rear dunes are also moderately developed in various locations. These dunes exhibit a discontinuous structure, with heights ranging from 5 to 7 meters along the east-west axis of the coast. A total of fifty-two (52) rivulets transport sediments into Chilika Lake. The Daya and Bhargavi Rivers are identified as the primary drainage contributors to the Sipasurubili to Brahmagiri mineral sand bar deposit, originating from the elevated regions of the Eastern Ghats and discharging into the sea at Girala Nala in Puri. Red sand patches can be observed near Satpada, Arkhuda, and several other locations. The sediment characteristics of the vast Mahanadi River basin, which is traversed by 33 tributaries that flow into the sea near these villages.

This study aims to investigate the characteristics of beach sand and heavy minerals, their distribution, modes of transport and deposition, and the economic implications of heavy mineral extraction for industrial applications. In order to understand the necessity of taking up and pursuing this project, it is advisable to provide a detailed explanation here. Indian Rare Earth (India) Limited [IREL] inaugurated its largest flagship Mining & Mineral separation facility, the Orissa Sands Complex (OSCOM), located on the East coast of India in Chhatarpur, Odisha, in 1986. Currently, IREL has achieved a processing capacity of approximately 10 lakh tons per annum of minerals, producing processed minerals such as Ilmenite, Rutile, Zircon, Sillimanite, and Garnet. Additionally, IREL has established a Rare Earths Extraction Plant in Odisha, capable of producing around 11,000 tons of Rare Earth Concentrate in the form of RE Chloride and related products. Given that mining has been conducted for over four decades, the quality of the raw sand has deteriorated, and the tailings produced have become enriched with the radioactive mineral monazite. Therefore, it is imperative to broaden the mining boundaries for sand extraction. Unfortunately, one side of Chhatarpur is bordered by city limits, while the other side is adjacent to Chilika Lake, making expansion in and around the Chhatarpur mining area unfeasible. Consequently, the alternative is to identify new resources within the same eastern coastal region. The beaches of Sipasurubili and Brahmagiri present significant potential for sand mining aimed extracting rare earth and critical minerals, as well as other industrial and economic purposes. In light of this, a comprehensive study has been proposed to investigate this area.

Grain size is a crucial physical characteristic of beach sediment and is a commonly used parameter for understanding the processes of sediment transport and deposition. The processes of degradation, or weathering, along with the movement of particles and their subsequent deposition in river basins and coastal areas, are significant. Weathering causes mountain surfaces to fragment into various rock fragments, which then roll down the slopes, accumulating as boulders and gravel, forming aeolian or alluvial deposits. During the tropical season, these materials are transported by rivers and accumulate along the riverbed as alluvial deposits[1-4]. Eventually, they are carried to the shoreline, where high tides and wind currents sort and concentrate individual mineral particles, resulting in beach placer deposits.

Studies on modelling, mineralogy and flow sheet development to recover individual heavy minerals and value additions from ilmenite, sillimanite, garnet, zircon, monazite etc. have been done by various researchers[3-13], but so far, any attempt on this aspect, such as sedimentary characters of Sipasurubili and Brahmagiri beach sand deposit, has not been made. It is important to mention here that the geomorphology of the Brahmagiri beach[3,5] is characterised by its location on the pedi plains and undulating plain area, rising from 600 feet above the surrounding plains. The area is known for its sedimentary placer deposits, which contain significant heavy minerals, indicating a rich mineralogical composition[14-20].

Understanding beach sediment size and textural characteristics is a valuable means of distinguishing between various depositional environments, both contemporary and historical. In view of this, many researchers have attempted to understand the depositional characteristics of sand, sorting, textural[8-20], and heavy mineral concentration[21-33] at different seasons and different depths at different locations. The distribution of beach sediment textures, along with wave action, influences the beach profile and shape, ultimately affecting its dynamic behaviour. Frequency distributions of sediment grain size, including standard deviation, sorting, skewness, and kurtosis, are commonly used to interpret sedimentation or deposition as they re-enter the natural environment. Grain size analysis is a traditional technique that yields additional insights into sediment transport, energy conditions, and depositional settings. Textural parameters such as grain-size distribution, standard deviation, sorting, skewness, and kurtosis are environmentally significant and instrumental in understanding the synsedimentary hydrodynamic factors that govern transportation and deposition within a basin. Numerous researchers, academicians, research students, and earth scientists have examined the textural characteristics of the west coast of India and the east coast up to Andhra Pradesh[1-7]. However, comprehensive studies specifically focusing on the Sipasurubili and Brahmagiri sand bar deposits with reference to textural and in-depth mineralogical studies have not been conducted. This study focuses on beach placer sediment characteristics and the distribution of heavy minerals in the coastal region between Sipasurubili and Brahmagiri, located on the east coast of Odisha, India, with an emphasis on industrial applications.

Materials and Methods

In the current research aimed at examining the sediment characteristics of the sediments from Sipasurubili to Brahmagiri beach (sample location map, Fig. 1), sand samples were systematically collected using the auger method along the coastline (Fig. 2). The entire sampling area was segmented into 24 stations distributed all along the three kilometres in the east-west direction and one kilometre in the north-south direction. The coast is straight longshore with a tidal bore.

A total of 120 samples were collected during each of the autumn, summer, and winter seasons, resulting in an overall collection of 360 samples from various zones (Figs. 3 and 4), including the shoreline (zone 1), backshore (zone 2), frontal dune (zone 3), central dune (zone 4), and back dune (zone 5). Each sample weighed 50 kilograms to facilitate comprehensive analysis. Heavy minerals were extracted from composite beach sand samples collected from various zones, specifically from the shore to the back dune (zones 1 to 5), during the summer months of May to August.

The samples were collected during three distinct seasons: autumn (January to April), summer (May to August), and winter (September to December). A total of 360 samples underwent wet size analysis using the IS sieve set. In contrast, a separate subset, a bulk composite sample, was processed using the Denver HG8 model laboratory spiral gravity separator to extract total heavy minerals (Fig. 4). Both total heavy minerals and light mineral quartz, including minor to trace amounts of feldspars and pyriboles, were analysed for size. Given that sink-float studies utilising organic liquids such as bromoform are both cost-prohibitive and hazardous to health, and considering that the amount of material obtained through the sink-float method would be inadequate for comprehensive size analysis and mineral identification, spiral concentration methods were employed instead. However, it is important to note that the bulk sample underwent sequential sink-and-float studies. The bromoform (2.89 sp. gr) sink is subjected to methyl iodide (3.3 sp. gr). Minerals with a specific gravity above 3.3 sp. gr are called here very heavy minerals, and minerals with a specific gravity

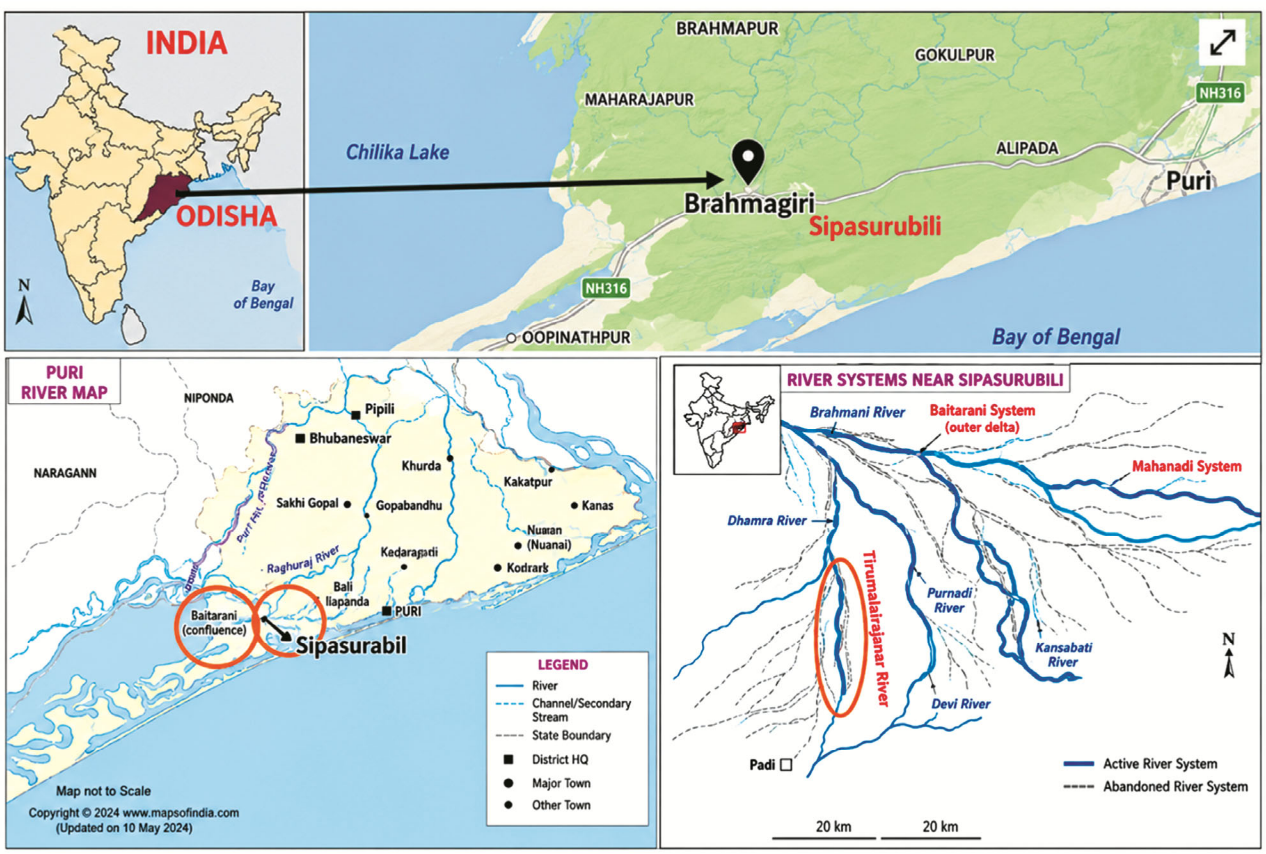

Fig. 1 — Sample location map (19°48′0″ N; 85°39′0″ E) with river system along the Sipasurubili to Brahmagiri beach coast

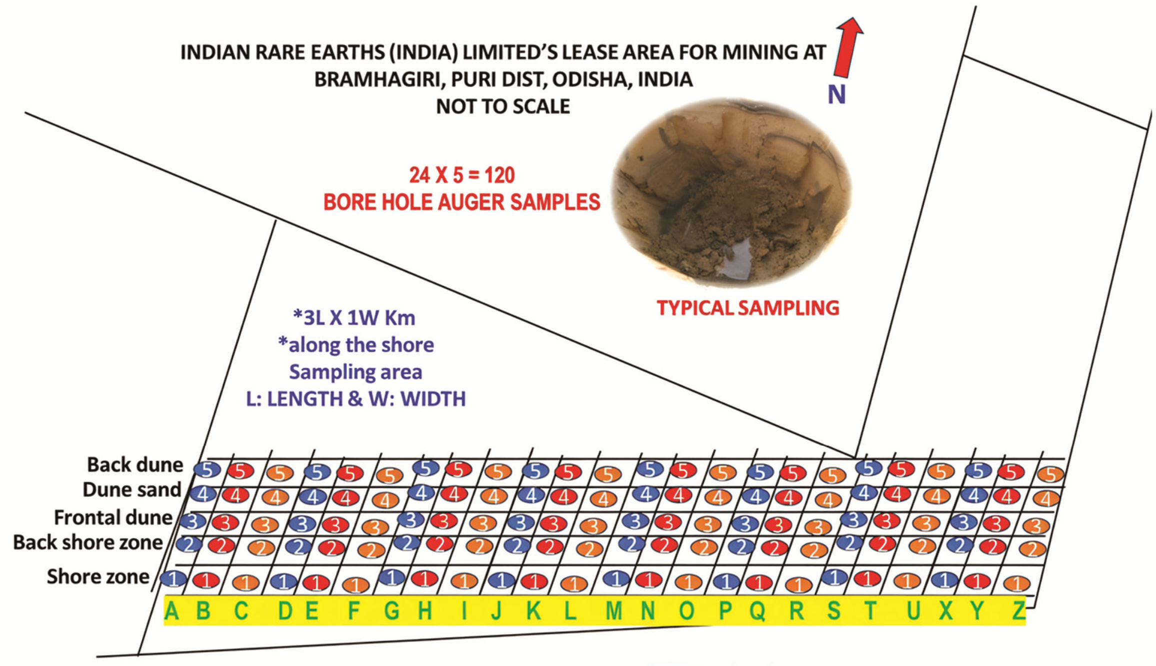

Fig. 2 — Sample (360 samples) collection points along the coast of Sipasurubili to Brahmagiri beach covering 3 km length E-W and 1 km in width N-S directions during three seasons for textural analysis

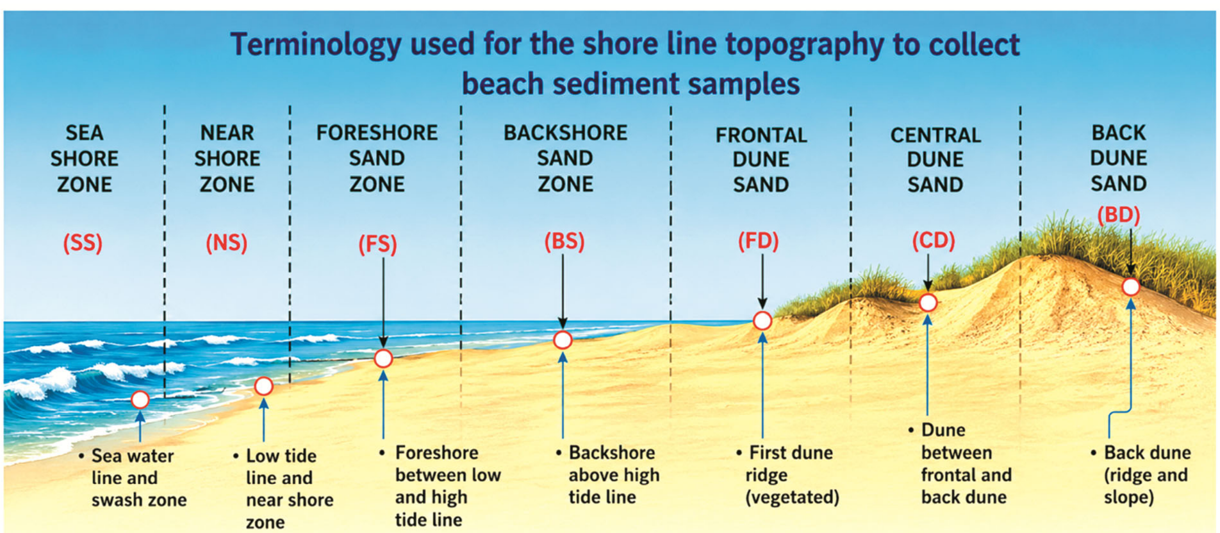

Fig. 3 — Samples collected from different shore zones sand deposit during three seasons along the cost of Sipasurubili to Brahmagiri beach

of less than 3.3 sp. gr but higher than 2.89 sp. gr are called very heavy minerals. The minerals that have properties of conducting characteristics are referred to as conducting minerals. Similarly, minerals that exhibit magnetic properties are referred to here as magnetic minerals.

In the spiral concentration process, the HG8 spiral was operated at a concentration of 15 % solids, utilising 20 kilograms of sample per batch. The heavy minerals obtained through HG8 spirals (Fig. 5) were subsequently processed to isolate ilmenite and rutile. At the same time, flotation techniques were employed to recover sillimanite, and magnetic separation was utilised for garnet and zircon extraction. The quantities of each individual mineral were assessed using a Leica petrological optical microscope (model no. Leica DM2500p), to count the number of grains of different minerals in a sample or from products or

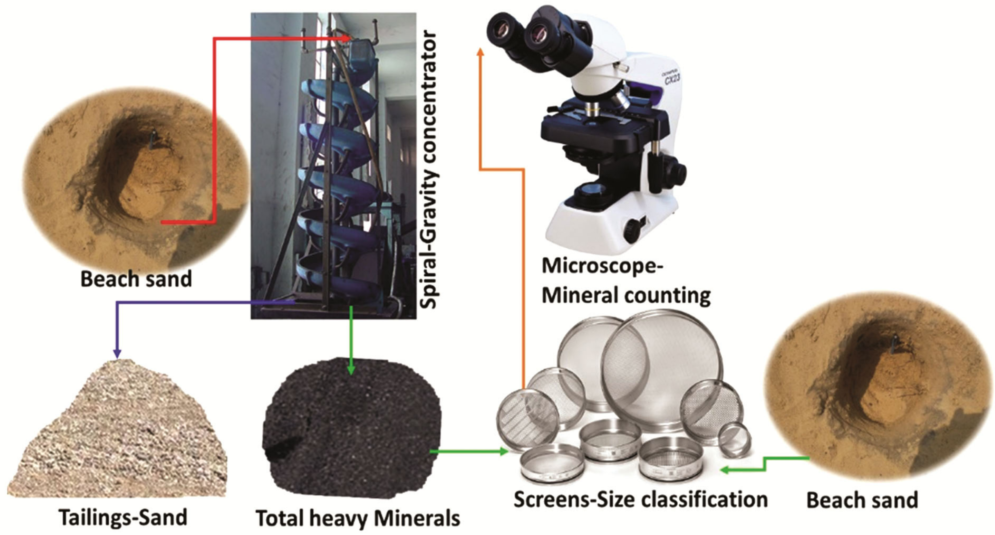

Fig. 4 — Schematic representation of experimental plan for textural study

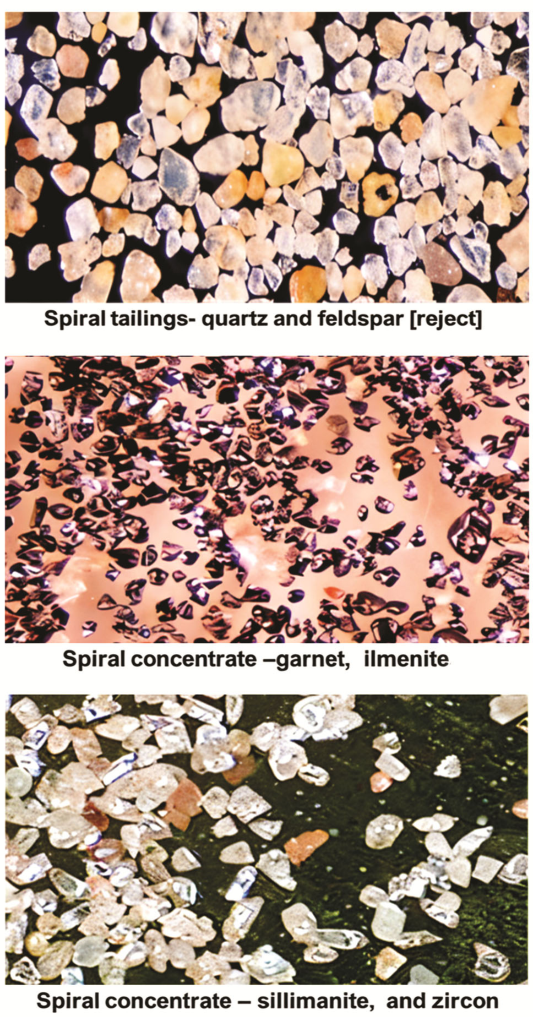

Fig. 5 — Spiral concentrator products, magnetics and non-magnetics, and rejects

close size range fractions (Fig. 5). The individual mineral weight% was calculated by using the following formula.

Individual grains × specific gravity of the mineral = mineral weight%

The size analysis was performed with standard IS wet sieves, and phi values for each size range were documented according to the established standard sheet. The study focused on three primary objectives: 1. The methodology for measuring grain size and its representation on a grade scale; 2. Techniques for quantifying grain size data and presenting it in both statistical and graphical formats; and 3. The genetic implications of the data. Various statistical methods, including the phi (Φ) statistic, were employed to assess the study's main objectives. The specific methods utilised included 1. Mean grain size (Mz), 2. Standard deviation (Sd), 3. Skewness (Sk), and 4. Kurtosis (kG).

$$\text{Mean grain size } (Mz\Phi) = (\Phi16+\Phi50+\Phi84)/3 \quad \dots (1)$$

$$\text{Standard deviation } (Sd) = (\Phi84-\Phi16)/4 + (\Phi95-\Phi5)/6.6 \quad \dots (2)$$

$$\text{Skewness } (Sk) = (\Phi16+\Phi84-2\Phi50)/2(84-16) + (\Phi95-\Phi5)/2*(\Phi95-\Phi5) \quad \dots (3)$$

$$\text{Kurtosis } (kG) = (\Phi95-\Phi5)/2.44(\Phi75-\Phi25) \quad \dots (4)$$

Results and Discussions

The study area comprises sand, silt, and gravel distributed across the surface of the back dune sand

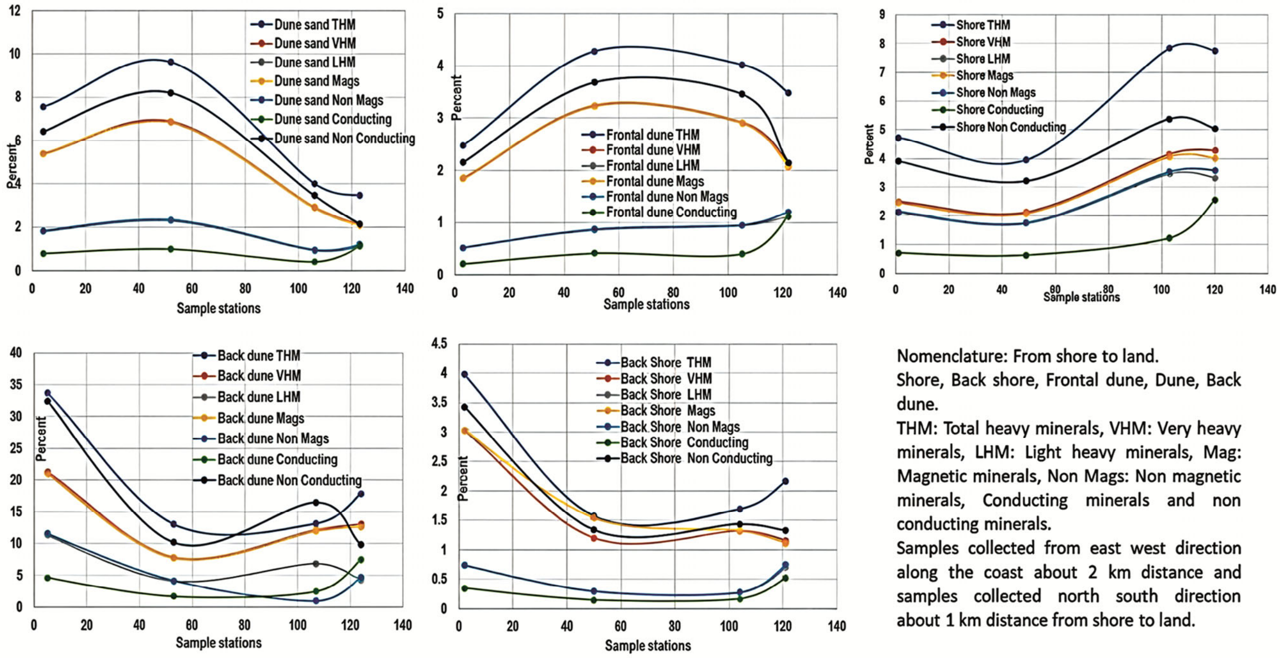

Fig. 6 — Physical and mineralogical characteristics of beach sand samples from shore to back dune, zone 1 to zone 5 (Composite sample collected during summer: May to August)

bar, which is encircled by compact clay. The immediate hinterland features the Eastern Ghats group of rocks, including an orthosite, granite gneiss, lateritic soil, and quartz reefs. Ilmenite, sillimanite, and garnets are the predominant components of industrial heavy minerals. In contrast, zircon, rutile and monazite, which are minor to trace amounts, are identified in the present sample by using a microscope. The data presented in Figure 6 indicate that the concentrate sample is primarily composed of titanium minerals, including ilmenite and rutile, followed by garnet and sillimanite, along with trace amounts of zircon and monazite. On the other hand, the spiral tailing sample predominantly consists of quartz, with minor to trace amounts of minerals such as pyroboles and feldspars.

The sediments from the Sipasurubili to Brahmagiri coast are known to contain placer heavy industrial minerals, including ilmenite, garnet, sillimanite, zircon, rutile, and monazite, which exhibit a range of sizes and morphological characteristics[3-5].

The concentration of Total Heavy Minerals (THM) varies at different points within the sample stations, ranging from the shore to the back dune (Fig. 6). It is also further seen that there is a noticeable reduction in mineral concentration observed in both shore and dune samples. This variation may be attributed to the dynamic shoreline influenced by high tides and powerful waves, which alter the concentration patterns. Notably, as illustrated in Figure 6, the distribution patterns of very heavy minerals, light heavy minerals, magnetic and non-magnetic minerals, as well as conducting and non-conducting minerals, exhibit significant differences from the shore to the frontal dune and dune sands. In contrast, the back dune sand does not show a concave profile in the graph for magnetic and non-magnetic, conducting and non-conducting, and very heavy to low heavy minerals; rather, these minerals tend to follow a more consistent concentration pattern. This finding suggests that the back dune sand is less affected by tidal waves and experiences minimal wind influence on heavy mineral concentration over time. It is evident from Table 1 that the concentrations of very heavy minerals, light heavy minerals, magnetic and non-magnetic minerals, as well as conducting and non-conducting minerals, exhibit a progressive trend from the Sipasurubili coast to the Brahmagiri coast across all specified concentration zones. Notably, the concentration of heavy minerals increases consistently along the coastline, with particularly high and stable levels observed in the back dune sand area. Therefore, it is advisable to extract samples from the back dune for mineral separation in processing plants.

Table 1 — Mineralogical characters of beach sand samples from shore to back dune (Composite sample collected during summer: May to August)

Sample	THM	VHM	LHM	Mags	Non-Mags	Conducting	Non-Conducting
Shore							
1	4.73	2.49	2.1	2.44	2.15	0.7	3.9
49	3.96	2.12	1.73	2.07	1.75	0.63	3.22
103	7.84	4.15	3.46	4.06	3.55	1.23	5.38
120	7.74	4.28	3.32	4.01	3.59	2.55	5.05
Back shore							
2	3.98	3.03	0.74	3.03	0.74	0.35	3.43
50	1.57	1.2	0.3	1.54	0.3	0.15	1.34
104	1.69	1.32	0.28	1.32	0.28	0.17	1.44
121	2.17	1.16	0.7	1.11	0.75	0.52	1.33
Frontal dune							
3	2.48	1.85	0.52	1.84	0.52	0.21	2.16
51	4.28	3.24	0.85	3.23	0.87	0.41	3.69
105	4.02	2.92	0.94	2.9	0.95	0.4	3.46
122	3.48	2.15	1.12	2.07	1.2	1.12	2.15
Dune sand							
4	7.56	5.41	1.8	5.38	1.83	0.79	6.44
52	9.63	6.9	2.3	6.85	2.34	0.99	8.21
106	4.02	2.92	0.94	2.9	0.95	0.4	3.46
123	3.48	2.15	1.12	2.07	1.2	1.12	2.15
Back dune							
5	33.75	21.29	11.29	21.02	11.56	4.66	32.44
53	13.09	7.85	4.1	7.74	4.21	1.77	10.2
107	13.18	12.15	6.87	11.99	1.03	2.54	16.5
124	17.86	13.11	4.26	12.63	4.74	7.5	9.87

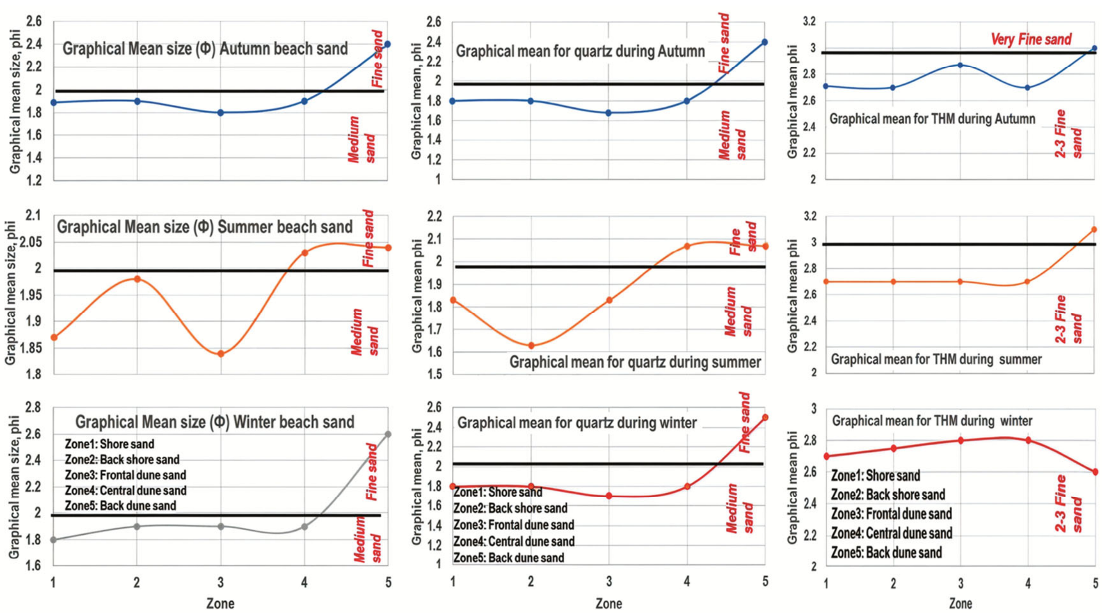

Fig. 7 — Graphical mean values phi of each zone for beach sand, quartz and THM during different seasons covering Sipasurubili to Brahmagiri coast 3 kms distance and 1 km across the land from South to North

Figure 7 represents the graphical representation of phi values corresponding to the grain sizes of sediments from Sipasurubili to Brahmagiri coast (ranging from shore to back dune sand), which were collected during the summer months of May to August, with the detailed data tabulated in Table 2. Additionally, the grain-size measurements for these sediments are illustrated in Table 3. The graphical

Table 2 — Graphic measures for phi values of the grain sizes of the sediments of Sipasurubili to Brahmagiri coast (Shore to back dune sand, samples collected during summer: May to August)

Sample No	Material	Φ95	φ84	Φ75	φ50	Φ25	φ16	Φ5
	Beach sand	0	2.75	2.5	1.95	1.3	0.9	0.9
Zone 1 Shore	Quartz	0	2.6	2.4	1.8	1.2	0.9	0.8
	Total heavy minerals	3.70	3.3	3.1	2.71	2.1	1.7	1.3
	Beach sand	0	2.6	2.5	1.9	1.35	1.11	0.8
Zone 2 Back shore	Quartz	0	2.8	2.4	1.8	1.2	1.09	0.8
	Total heavy minerals	3.75	3.3	3.1	2.7	2.1	1.90	1.20
	Beach sand	0	2.6	2.5	1.9	1.3	1.02	0.8
Zone 3 Frontal dune	Quartz	0	2.8	2.4	1.7	1.2	1.01	0.8
	Total heavy minerals	3.75	3.3	3.1	2.7	2.05	2.1	2.1
	Beach sand	0	2.6	1.9	2.5	1.3	1.0	0.8
Zone 4 Central dune	Quartz	0	2.8	1.7	2.4	1.2	1.01	0.8
	Total heavy minerals	3.75	3.3	2.7	3.1	2.05	1.7	1.2
	Beach sand	0	2.6	1.91	2.5	1.32	1.01	0.8
Zone 5 Back dune	Quartz	0	2.8	1.79	2.4	1.2	1.01	0.8
	Total heavy minerals	3.75	3.3	2.7	3.1	2.1	1.8	1.3

Table 3 — Graphic measures from the grain sizes of the sediments of Sipasurubili to Brahmagiri coast (Shore to back dune sand samples collected during summer: May to August)

Sample No	Material	Median size	Graphical mean size (Φ)	Sorting-standard deviation (Ō)	Skewness	Kurtosis	Remarks				
							Median size	Graphical mean size (Φ)	Sorting-standard deviation (Ō)	Skewness	Kurtosis
Zone 1 Shore line sand	Beach sand	1.95	1.87	0.326136	-0.58	-0.30738	MS	MS	VWS	HSD	VPK
	Quartz	1.80	1.83	0.303788	-0.54	-0.27322	MS	MS	VWS	HSD	VPK
	Total heavy minerals	2.71	2.57	0.763636	6.49	0.983607	FS	FS	MS	HSD	MK
Zone 2 Back shore sand	Beach sand	1.90	1.983	0.251288	-0.32	-0.285	MS	MS	VWS	HSD	VPK
	Quartz	1.8	1.633	0.306288	-0.55	-0.273	MS	MS	VWS	HSD	VPK
	Total heavy minerals	2.7	2.913	0.736364	7.01	1.045	FS	FS	MS	HSD	MK
Zone 3 Frontal dune sand	Beach sand	1.9	1.84	0.274	-0.40	-0.27322	MS	MS	VWS	HSD	VPK
	Quartz	1.7	1.83	0.326	-0.65	-0.27322	MS	MS	VWS	HSD	VPK
	Total heavy minerals	2.7	2.70	0.550	-5.55	0.644028	FS	FS	MWS	HSD	VPK
Zone 4 Dune sand	Beach sand	1.9	2.03	0.279	-0.03	-0.546	MS	MS	VWS	HSD	VPK
	Quartz	1.8	2.07	0.326	-0.30	-0.656	MS	MS	VWS	HSD	VPK
	Total heavy minerals	2.7	2.70	0.786	7.04	1.608	FS	FS	MS	HSD	VPK
Zone 5 Back dune sand	Beach sand	2.5	2.04	0.276	-0.03	-0.556	FS	FS	VWS	HSD	VPK
	Quartz	2.4	2.07	0.326	-0.26	-0.556	FS	FS	VWS	HSD	VPK
	Total heavy minerals	3.1	2.73	0.746	-6.65	1.673	VFS	FS	MS	HSD	VPK

MS: Medium size sand, FS: Fine size sand, VFS: Very fine size sand, VWS: Very well sorted, WS: Well sorted, HSD: Highly skewed distribution

mean size for zone 1 (zone 1 is the shore zone, mentioned in the earlier section), which includes beach sand, quartz, and total heavy minerals, indicates that the mean size of quartz sand is nearly equivalent to that of beach sand, while the heavy minerals exhibit a different trend. It is anticipated that the lighter, coarser mineral quartz, despite not being sub-rounded, coexists with fine heavy minerals that are sub-rounded to rounded due to gravity concentration and various transport mechanisms. Observations from zone 1 (shore sand) to zone 5 (back dune sand) reveal that the mean sizes of quartz and beach sand remain closely aligned, whereas the heavy minerals show greater variability. Notably, there is a significant variation in particle size from zone 1 (shore sand) to zone 5 (back dune sand). Given that the trends in beach sand and its lighter mineral, quartz, align with respect to transportation and deposition, the subsequent discussion will focus solely on quartz in conjunction with heavy minerals.

The mean beach sand grain sizes categorises the samples into various types, including very coarse sand, coarse sand, medium sand, fine sand, very fine sand, silt, and clay[12,20,29,34-36]. According to the current study, values of mean grain size (Mz) in Φ ranging from 1 to 2 indicate medium grain size, while values of mean grain size (Mz) in Φ ranging from 2 to 3 correspond to fine-grained sand. Furthermore, as illustrated in Table 3, the mean size of beach sand, quartz, and heavy minerals determined from wet size analysis, as explained in the materials and methods, reveals that fine sand is present above a graphic mean

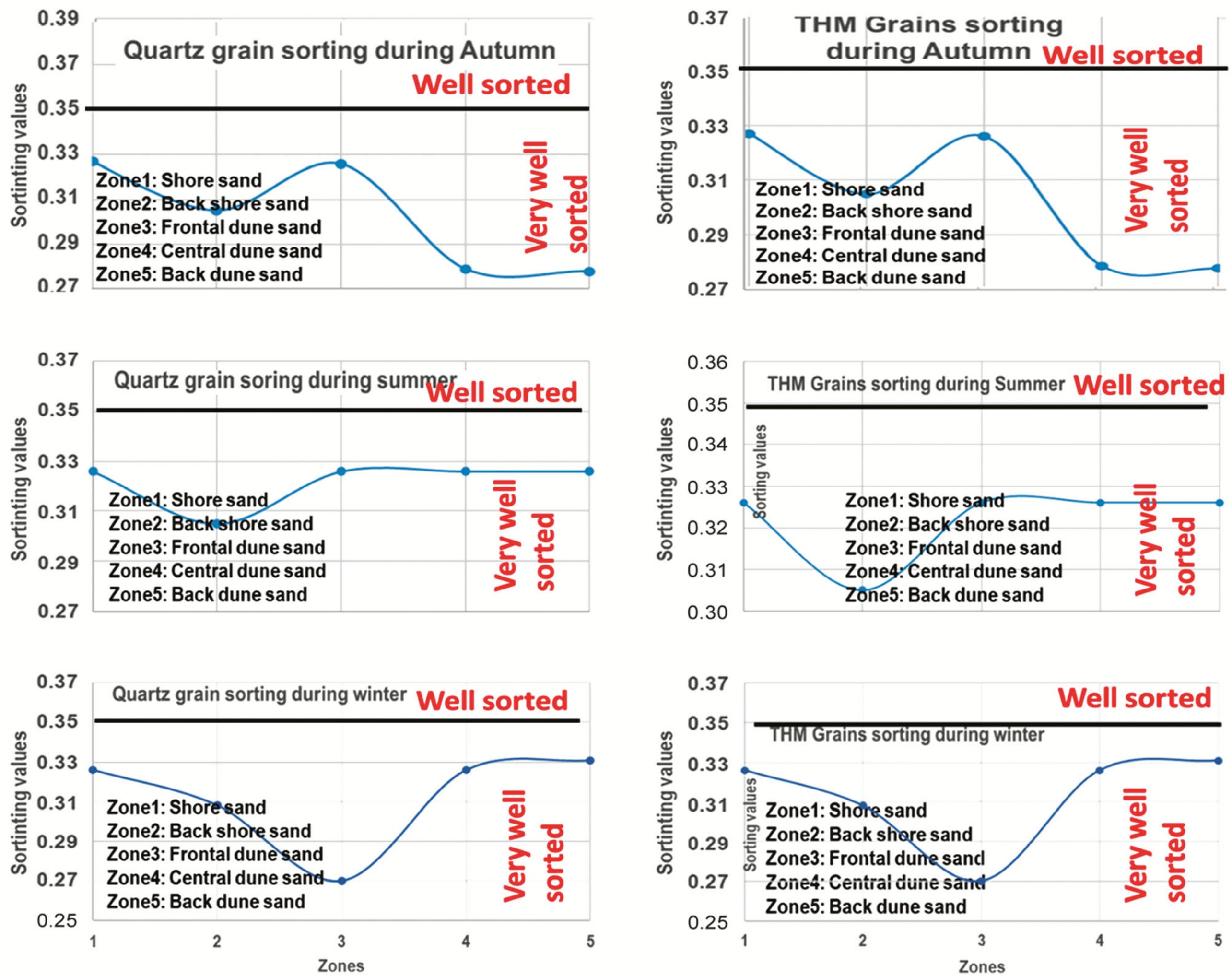

Fig. 8 — Standard deviation/sorting values of each zone for beach sand, quartz and THMs during different seasons covering Sipasurubili to Brahmagiri coast 3 kms distance

of 2 (Mz) in Φ. In contrast, medium sand is found below this threshold. Notably, the distribution of fine sand within heavy minerals is significantly more pronounced than that in beach sand and quartz. Sorting values, as examined by various researchers, categorise mineral grains into classifications such as very well sorted, well sorted, moderately well sorted, moderately sorted, poorly sorted, very poorly sorted, and extremely poorly sorted[10,20,35,37-42]. In this study, it is noteworthy that both quartz and total heavy minerals exhibit well-sorted characteristics, with observations of heavy minerals being particularly significant (Fig. 8).

Skewed particles, whether analysed mathematically or graphically, indicate a distribution where values are either less than one or greater than one, which is classified as a highly skewed distribution[35,43,46]. Distributions falling between -1 and -0.5 or between 0.5 and 1.0 are categorised as moderately skewed, while values ranging from -0.5 to 0.5 are considered approximately symmetric (Fig. 9). In the current study, as detailed in Table 3, the skewness values for quartz and total heavy minerals reveal that both exhibit a highly skewed distribution of particles. The kurtosis values are categorised as very platykurtic, platykurtic, mesokurtic, leptokurtic, and extremely leptokurtic. The findings indicate that quartz demonstrates only a mesokurtic distribution, whereas total heavy minerals display both mesokurtic and platykurtic characteristics when examined across different zones (1 to 5) from the shore to the back dune sand, particularly during the summer season (Fig. 10).

The sampling sites reveal concentrations of heavy minerals, which appear as discontinuous Heavy

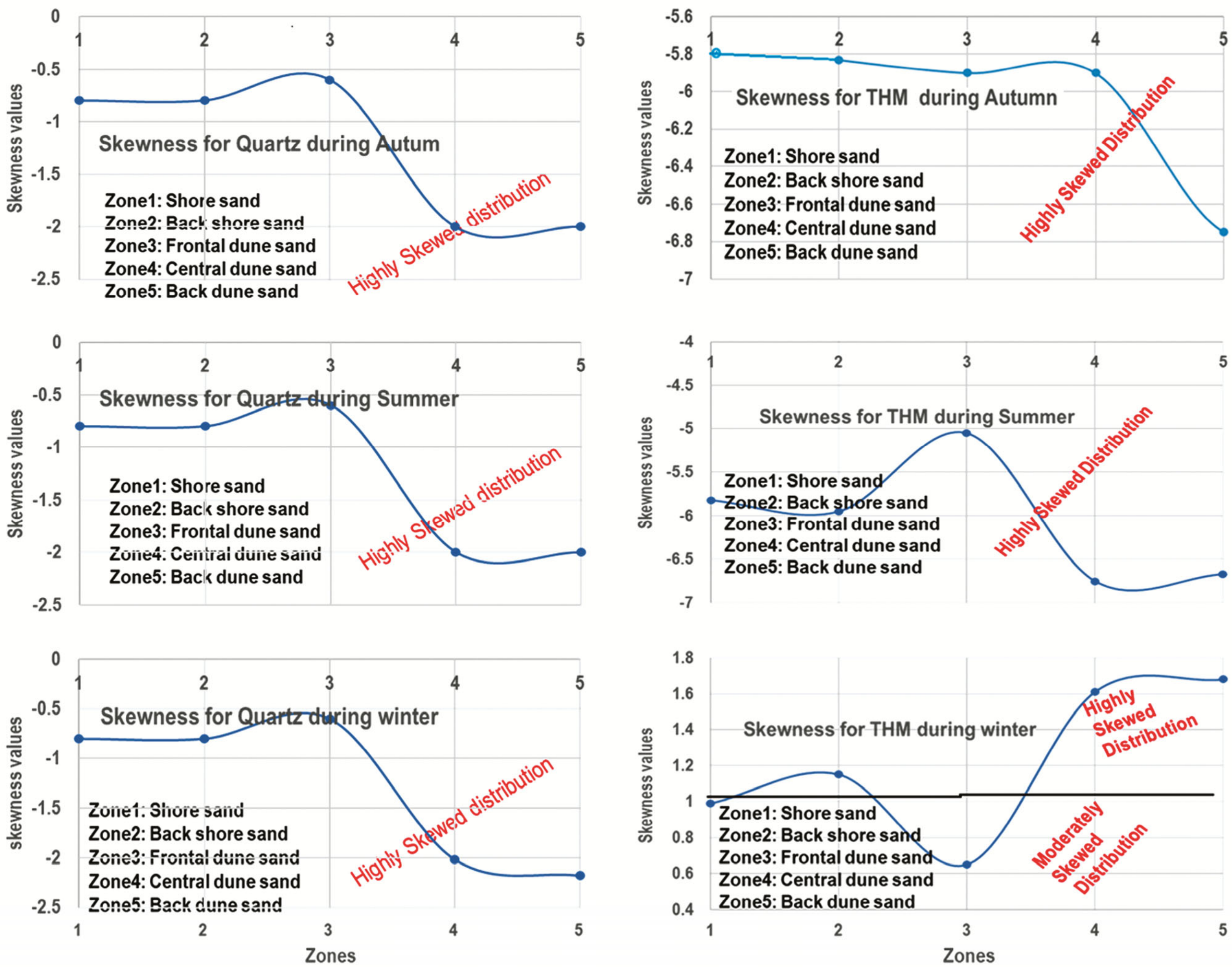

Fig. 9 — Skewness values phi of each zone for quartz and THMs during different seasons covering Sipasurubili to Brahmagiri coast 3 kms distance

Mineral (HM) bands within the predominantly quartz sand of the beach. The study investigates the influence of tropical and sub-tropical variations across three distinct seasons (autumn, summer, and winter)[47-52] focusing on sedimentology and the concentration of heavy minerals at the Sipasurubili and Brahmagiri placer sand deposits. The findings of the investigations on mineralisation (THM) behaviours across all seasons, as well as in shore-to-back dune sand deposits, are illustrated earlier in Figures 7 to 10. The analysis of particle mean size across the different seasons' autumn, summer, and winter, encompasses various zones, including shore sand, back shore, frontal dune, central dune, and back dune sand, as depicted in Figure 8. The data reveal that medium and fine sands are predominantly present across all zones, from shore sand to back dune sand along the coast, indicating a northward deposition trend. Throughout the year, waves predominantly originate from the south and southeast along the lagoon coast, thereby facilitating continuous northward longshore sediment transport[53]. Notably, the concentration of heavy minerals is more pronounced in winter, particularly in fine sand, compared to summer deposits. This observation supports the concept that during the summer season, the present investigation area is normally associated with high winds associated with cyclones. Hence, the concentration pattern of heavy minerals is always consistent. During the winter season, this area is covered with pleasant climaticconditions[53-59].

Furthermore, the presence of very fine and fine heavy mineral concentrations is clearly illustrated in Figure 7. In the present study area, the mean value of

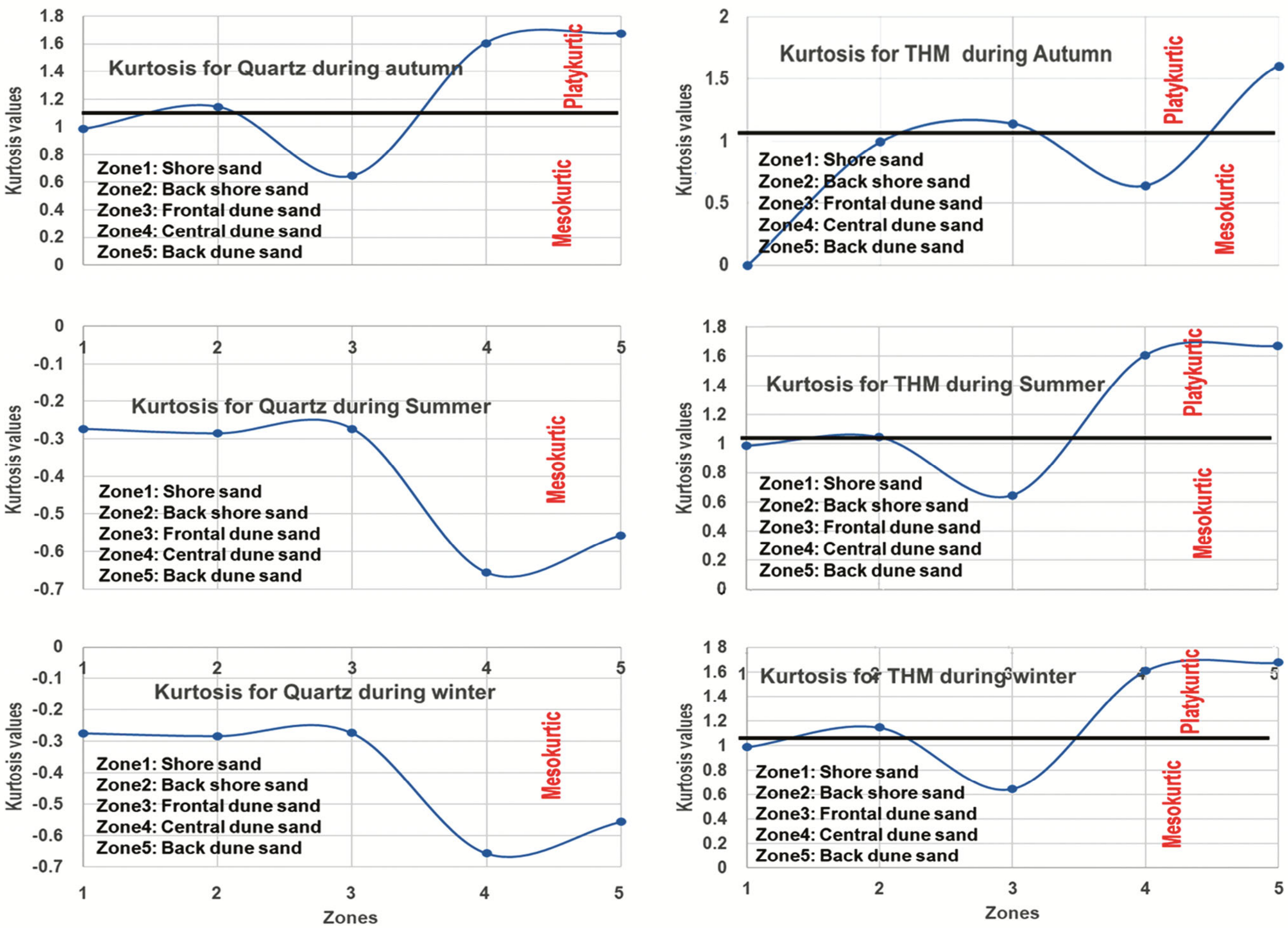

Fig. 10 — Kurtosis values phi of each zone for beach sand, quartz and THMs during different seasons covering Sipasurubili to Brahmagiri coast 3 kms distance

collected samples is shown in a range from 1.8 to 2.6 Mz Φ, indicating a prominent distribution of medium sand to fine sand and very fine sand, especially in the autumn for heavy minerals (Fig. 7). The mean value demonstrates a similar trend in all these areas. The distribution of finer sand to very fine sand in a few locations in the study area may have happened from the dislodging of coarser, lighter sediments by the panning activity of high-speed waves. Medium sand is observed at most locations, indicating moderate wave energy conditions in the region.

The analysis of quartz and heavy mineral sorting across all seasons from Sipasurubili to the Brahmagiri coast indicates that the grains are generally well sorted to very well sorted, except for heavy mineral concentrations observed during the winter season (Fig. 8). In winter, only very well sorted heavy mineral grains are present across all concentration zones. This phenomenon can be attributed to the sandy bar located between Sipasurubili and Brahmagiri, which lies near the Chilika lagoon catchment area. This region has been affected by a series of tropical cyclones, ranging from minor to severe, impacting the Odisha coast, including the super cyclonic storm of October 29, 1999, the very severe tropical cyclone Phailin on October 12, 2013, and Hudhud on October 12, 2014, among others. These cyclones significantly affect heavy mineral grains in the sediment, which exhibit markedly different hydrodynamic properties from lighter minerals such as quartz and feldspar. Due to their differing densities, grain sizes, and shapes, heavy minerals are typically more difficult for flowing water to transport than lighter minerals, resulting in the formation of lag deposits where heavy minerals become concentrated as lighter minerals are selectively removed. The formation of lag deposits in streams is clearly seen in Figure 11. The analysis of

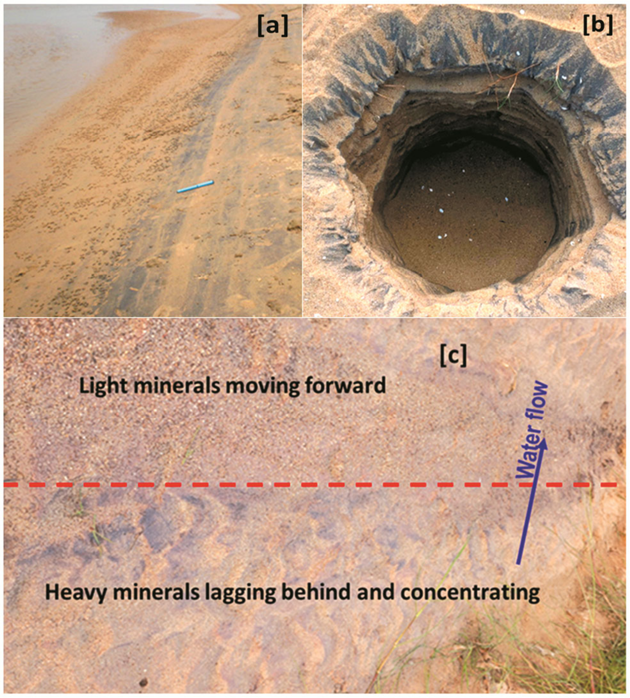

Fig. 11 — Morphological features of beach sand bars: a) Beach sand along the shore line, b) Vertical section of the beach sand (Heavy minerals band along the sand bar and in vertical section alternative layers), and c) Formation of lag deposits

the sorting values from the current studies indicates the characteristics of sediment types and their transportation methods. The sorting phi values (Ō) ranged from 0.27 to 0.33 (Fig. 8), suggesting that the deposition of sediments, which are classified as well- to very well-sorted, is influenced by several factors. These include the gentle slope of the beach, the oscillatory movement of sand grains due to winnowing, and the reworking of the beach edges[45]. Furthermore, sorting is associated with the deposition mode and is contingent upon variations in kinetic energy[43]. Furthermore, many researchers[14,25,34,37,46-48,60-64] have explained the seasonal variation and its influence on sorting, settling, or concentration of heavy minerals, which are similar to the present investigations.

The skewness values illustrated in Figure 9 for quartz and THM across various seasons indicates that quartz particles exhibit a highly skewed distribution throughout all seasons[44] alongside heavy minerals. The distribution of heavy minerals shows similar skewness in both autumn and summer; however, this is not the case in winter, as observed across different concentration zones. The heavy mineral assemblage across various sand units, namely shore, back shore, frontal dune, central dune, and back dune, suggests that the sediments originate from the Eastern Ghat suite of rocks, specifically the khondalite and charnokite groups, influenced by different seasons and transport mechanisms to the sea. These observations are similar to the findings reported by other researchers[31,35,44].

According to the classification established by Folk & Ward, 1957, the skewness values of both sands and heavy minerals predominantly exhibit symmetrical characteristics[44,65] with a tendency towards positive skewness in winter heavy mineral concentrations, as illustrated in Figure 9. This symmetrical skewness suggests the influence of winnowing processes and a moderately energetic environment. In contrast, the observed negative skewness indicates high-energy conditions that prevent sediment deposition, as noted by Duane[44]. Generally, tropical cyclones occur along the Odisha coast during the summer and autumn. During these periods, the combination of high tides, energetic waves, and continuous wave fluctuations can alter grain concentration patterns of grains, including those of lighter and heavier minerals. However, this effect is not pronounced during winter, particularly concerning heavy minerals. Consequently, the distribution pattern of heavy minerals appears distinct in winter.

The kurtosis values for quartz and total heavy minerals extracted from beach sand across various seasons and locations, including the shore, back shore, frontal dune, central dune, and back dune, are illustrated in Figure 10. Kurtosis serves to characterise the nature of sediments, ranging from mesokurtic to very leptokurtic. This study clearly indicates that the kurtosis values for quartz during autumn exhibit both mesokurtic and platykurtic characteristics. This finding aligns with the heavy mineral concentration observed in the same season. The trend remains largely consistent for heavy mineral concentration across all seasons. However, for quartz, only mesokurtic is noted during the summer and winter months. A normal Gaussian distribution is characterised by a kurtosis (kg) of 1.00, indicating that the sorting in the tails is equivalent to that in the central portion. If a sample curve demonstrates better sorting in the central region than in the tails, it is classified as excessively peaked or leptokurtic; conversely, if the tails are better sorted than the central portion, the curve is considered flat-peaked or platykurtic[65]. The Graphical Kurtosis (KG) used here is based on the formula given by Folk &

Ward, 1957. The kurtosis varied in the study area from -0.273 to 1.68. Based on Folk's classification, the studied samples exhibited mesokurtic and platykurtic characteristics, and the kurtosis plots indicated a prevalence of low-to-high energy[11]. Normal curves have a kurtosis of 1.00, while leptokurtic curves exceed 1.00, and platykurtic curves fall below 1.00. Consequently, textural parameters such as grain-size distribution, standard deviation, sorting, skewness, and kurtosis are environmentally significant and instrumental in understanding the synsedimentary hydrodynamic factors that influence transportation and deposition within the sandy bar from Sipasurubili to the Brahmagiri sand basin.

The current study indicates that the mean size is utilised to determine the dominant grain size. The standard deviation reflects the sorting characteristics of particle grains, soil, or sediment. Skewness assesses the degree of asymmetry in the distribution, while kurtosis evaluates the nature of sediments, ranging from platykurtic to very leptokurtic.

Thus, it can be inferred from research by various scholars that, in India, the rainy season, encompassing both the South-West and North-East monsoon periods, is characterised by rapid erosion and sediment transport[50,51]. Conversely, during the non-rainy seasons, processes of accumulation, sorting, and segregation are observed at depositional sites[49-51]. Furthermore, the deposition of heavy minerals occurs in various marine micro-environments, including dunes, berms, back shores, and foreshores, with mineral characteristics, such as shape, size, and density, playing a significant role[12]. Following deposition, lateral transport and selective sorting processes further facilitate the accumulation of heavy minerals, resulting in placer deposits along the coastline[52].

Sediment plays a significant role in documenting landform formations. Various statistical parameters, such as graphical mean grain size (Mz), standard deviation (Sd), skewness (Sk), and kurtosis (kG), are used to assess sediment textural characteristics[44]. The mean grain size is being used to find out the dominant grain size. Standard deviation shows the sorting nature of soil or sediment. Skewness measures the degree of skewness, and kurtosis quantifies the sediment nature, which ranges from mesokurtic to very leptokurtic.

The characterisation of sediments from various coasts of India has been examined by numerous researchers[9,10,18,22,47,54-64], but this study selectively focuses on certain coasts based on their findings. The sediment characteristics of several Indian coasts, including Someshwar, Diga, Veleneshwar, Sarada, Gosthani, Besant Nagar, Sathurangapattinam, Tirumalairajanar, Chinnavilai, Erayumanthurai, Rameswarm, Paradep, Kalpakam, Karikal, Nagore, and Visakhapatnam, indicate that, in general, the mean grain sizes from the fore zone to the back dune sand show that the mean sizes of quartz and beach sand are closely aligned, while the heavy minerals exhibit greater variability. The mean size of heavy minerals such as ilmenite, garnet, sillimanite, rutile, zircon, and monazite is finer than that of the gangue mineral quartz. In the Sarada River area[47] heavy minerals are associated with fine fractions. The sediments in the Tirumalairajanar River are predominantly medium to coarse-grained and moderately sorted[54]. Grain size analysis from Besant Nagar revealed fine- to medium-grained sandy sediment with very well- to moderately sorted characteristics, indicating reworking of beach edges accompanied by unimodal to trimodal sediment distribution[22,58]. The beach sediments of Chinnavilai and Erayumanthurai in the Kanyakumari district display medium-grained, moderately well-sorted, unimodal, and occasionally bimodal characteristics, with mesokurtic, leptokurtic, and platykurtic distributions[58]. At Paradeep, the backshore regions primarily consist of medium sand, with changes being relatively invariant across seasons[57]. The percentage of fine sand is higher in January compared to September due to the prevalence of calm wave conditions. The mean grain size decreases in the backshore region and increases in the foreshore region from south to north along the coast, indicating the dominance of aeolian transport. The variations in grain size characteristics along the Visakhapatnam beach are believed to have been influenced by wave refraction and longshore currents acting on the surface of heavy mineral grains[14, 25, 41]. The grain micro-textures of the heavy minerals show the dominance of mechanical features, as these grains were subjected to long-distance transport. The micro-textures from the coastal area also show the effect of mechanical and chemical erosion.

The finely skewed and symmetrical characteristics of sediments at Chinnavilai suggest the existence presence of both high- and low-energy conditions, resulting in a mixed distribution of coarse and fine sediments[17,38,58,65]. These features of the Sarda River area also point to a high-energy environment. Reports indicate that the steep waves during the south-west monsoon months at Someshwar exhibit high energy levels[18,47]. The sediments are primarily moderately sorted in the backshore region and moderately well sorted in the foreshore area. The presence of a relatively high proportion of mesokurtic sediment suggests that the beaches along Kalpakkam generally maintain a uniform energy environment[56]. The sorting coefficient values presented in this study indicate that the beach sand and heavy minerals are well sorted. At Someshwar, the sorting coefficient values are predominantly < 2.5, which signifies that the beach sand in this region is well sorted throughout the year[47]. The Diga coast is characterised by a dominance of fine-grained sediments and a well-sorted platform.[11] The proportion of medium sand and fine sand is significantly higher at Velneshwar, a sandy beach, compared to very coarse sand and gravel. The sediment characteristics in the Sarada area range from moderately to well sorted[11,47]. At Kalpakam, the sediment samples reveal a sorting range from very well sorted (0.18 ø) to poorly sorted (1.18 ø), with sorting characteristics diminishing as wave energy increases[56]. The results from the skewed distribution analysis indicate that quartz exhibits a mesokurtic distribution, while total heavy minerals show both mesokurtic and platykurtic traits. The sediments located at the Tirumalairajanar River are characterised as fine- to coarse-skewed and exhibit leptokurtic to mesokurtic properties. Predominantly symmetrical and mesokurtic sediments are found along the coast at Someshwar, indicating that the sediments are well sorted in the central portion of the sediment distribution[11,54].

The current research on sediment samples collected from Sipasurubili to the Brahmagiri coastal beach presents the overall findings alongside other researchers' studies on sediment samples from different coastlines. The results from the skewed distribution analysis show that quartz exhibits only a mesokurtic distribution, while total heavy minerals display both mesokurtic and platykurtic characteristics. An attempt is made to further compare the results of these investigations with some of the other resources. A study conducted on the beach placer deposits of India[60], focusing on their distribution, mineralogy, and sustainable mining practices concerning placer ilmenite indicates that these deposits are located along both the East and West coasts of India, with the Total Heavy Mineral content (THM) ranging from 12 to 15 % by weight. Ilmenite constitutes nearly 40 % of this total heavy mineral content. It is recommended that environmentally sustainable mining and processing methods be adopted to mitigate environmental impact. This study provides support for the current investigation, particularly regarding total heavy minerals and recommendations for mining operations. In a similar vein, the research conducted on the exploration of strategic placer mineral deposits along a fluctuating shoreline, specifically the depositional environment and mineralogical characterisation of the NE Odisha coast placers, India, indicates that detailed experimental studies reveal the THM grade of the heavy mineral assemblages to consist of 55 % ilmenite, 25 % sillimanite, 5.9 % rutile, 1.2 % garnet, 0.5 % zircon, and 0.4 % magnetite[61]. Texturally, higher concentrations of heavy minerals are extracted from the +75 µm and +125 µm size fractions, while the 425 µm size fraction exhibits the lowest THM. The range of graphic mean sizes (Mz) spans 2.19 to 2.60 (Φ), supporting the notion of sediment deposition under low-energy conditions along the fluctuating shoreline of the Chandipur coast[57,66]. The current investigation clearly demonstrates, through detailed analysis, that the beach placer deposits, despite containing some inferior minerals, also encompass all industrial minerals of significant economic value. Furthermore, the textural analysis corroborates the presence of minerals within the size range of 420 microns to 75 microns. According to the present study, mean grain size (Mz) values in Φ that range from 1 to 2 signify a medium size, whereas mean grain size (Mz) values in Φ that fall between 2 and 3 are indicative of fine sand. Additionally, the mean size of beach sand, quartz, and heavy minerals, as determined by sieving, indicates that fine sand is found above a graphic mean of 2 (Mz) in Φ. The relationship between heavy mineral placer deposits and the hinterland rocks of southern Kerala, has been elucidated and a novel approach has been proposed for establishing a source-to-sink link based on the chemistry of garnets[62]. The present study encompasses the geological and geomorphological context and the mineralogical characteristics of hinterland rocks, to trace their association with placer deposits. It is acknowledged that garnet is the predominant heavy mineral found in placer sediments and in source rocks of varying ages and petrogenetic affinities. The current investigations align with the observations, particularly regarding the presence of garnets sourced from khondalites.

A study conducted on the geochemistry of heavy mineral sands from Garampeta to Markandi Beach[63], located on the southern coast of Odisha, India indicate that the high concentrations of Rare Earth Elements (REE) and radioelements, attributed to placer monazite, reveal that the primary elements present are the radioactive mineral monazite and rare earth elements. The average REE concentration in the beach sand samples is approximately four times greater than the average crustal concentration. Additionally, the beach sand contains heavy minerals of economic significance, with monazite being a source of rare earth elements. The elevated cerium levels suggest that the garnets originate from khondalite rocks. As reported by other researchers[64] in their investigation on the provenance of heavy minerals in the territorial waters off Palur–Malud, Odisha, India, characterisation through petrological and geochemical studies reveals the primary source of garnet to be high-grade meta-sedimentary rocks, with a minor contribution from charnockites. The heavy minerals found in the sediments of this area are angular to subrounded, indicating mechanical abrasion and collision. Consequently, the main transporting agent for the continental placer resources in this region is the Rushikulya River, supplemented by contributions from Chilka Lake. Notably, the current study aligns with the findings of Singh *et al.*[64], as the garnets are derived from khondalite rocks, and the particles are sub-rounded to rounded. It is also posited that the minerals are transported by the Rushikulya River and deposited in Chilka, crossing Sipasurubili and Brahmagiri on the East coast.

Conclusion

The present investigation demonstrates that the coastal sediments between Sipasurubili and Brahmagiri are predominantly composed of medium- to fine-grained sands exhibiting generally good sorting, with seasonal variations governed by hydrodynamic conditions. Quartz is the dominant light mineral and therefore closely reflects the overall grain-size characteristics of the bulk sediment, whereas the heavy mineral fraction is mainly composed of ilmenite, sillimanite, and garnet, with rutile, zircon, and monazite occurring as subordinate but economically important constituents. The observed variations in grain-size parameters, sorting, skewness, and kurtosis indicate the influence of wave action, tidal fluctuations, and monsoon-controlled littoral processes on sediment transport and deposition. The provenance of the heavy minerals suggests derivation from granulite gneiss, charnockites, migmatites, and basic dykes, followed by fluvial transport and subsequent hydraulic sorting and concentration along the coast through longshore currents and swash–backwash processes.

A comparative evaluation with published studies from major coastal regions of India reveals that sediment texture and heavy mineral enrichment are consistently controlled by the combined effects of seasonal wave energy, river discharge, tidal action, wind regime, and longshore sediment transport. Although the concentration and distribution of heavy minerals vary spatially according to source-rock lithology and local coastal dynamics, the dominant depositional mechanisms remain similar. The substantial occurrence of economically significant placer minerals, including ilmenite, garnet, sillimanite, rutile, zircon, and monazite, confirms the high mineral resource potential of the Sipasurubili–Brahmagiri coast. These findings provide valuable insights into sediment provenance, coastal sedimentary processes, and placer mineral enrichment, and establish a scientific basis for future exploration, sustainable resource management, and the strategic recovery of critical minerals from India's coastal placer deposits.

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Conflict of Interest

There is no conflict of interest in this manuscript.

Author Contributions

RBR: Sample collection, data interpretation, and submission of manuscript; SR: Data interpretation; RS: Writing of the manuscript; BM & DS: Sample collection; and SSS: Data interpretation.

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