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Seasonal Variations in Textural Characteristics and Sedimentary Environments of the Gaonkhadi Beach Sediments, Ratnagiri District, West Coast of India

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Abstract

The seasonal variations in the textural parameters of beach sediments were studied along the Purangad-Gaonkhadi Coast of the Ratnagiri District, Maharashtra, India. During the pre-monsoon (PRM) season, the foreshore sediments comprise fine sand to medium sand, while the backshore, raised beach (Berm) and foredune sediments show fine sand characteristics. The PRM foreshore, backshore, raised beach (Berm) and foredune sediments are well-sorted to moderately well-sorted. The foreshore sediments show symmetrical to strongly fine skewed whereas, backshore sediments are fine skewed to strongly fine skewed. The foreshore and backshore sediments in the post-monsoon (POM) season are comprised of coarse-grained sands, whereas raised beach and foredune sediments contain fine-grained sand. The foreshore sediments are poorly sorted to very poorly sorted, while the backshore and raised beach sediments are moderately poorly sorted. The linear discriminant analysis (LDA) plots of the sediments fall in a shallow marine environment, while few fall in a beach shallow environment. The XRF studies indicate a high concentration of 'Fe' in the northern part while it decreases towards the southern part along the beach. The 'Fe' concentration also increases cross-shore from foreshore to backshore. The 'Ti' concentration also shows an increasing trend from the foreshore to the backshore zone. The mud flat samples have indicated the presence of kaolinite, illite, smectite, and chlorite. The concentration of kaolinite and illite is higher than that of smectite and chlorite from north to south in the study area. The waves and currents along the Gaonkhadi Coast of the Ratnagiri District are formed under high energy conditions during the SW monsoon and affected erosion with a strong winnowing process.

Keywords: Grain Size, Linear Discriminant Functions, CM Plots, Depositional Sedimentary Environment, West Coast of India

Introduction

Grain size studies of sediments have provided significant information about beach dynamics and depositional environment. Their textural analysis displays fluctuations in mean size, standard deviation, skewness and kurtosis due to variations in wave energy and the extent of turbulence affecting the beach environment during the cross-shore and alongshore movement of sediment (Sarvanana and Chandrasekhar, 2010). The southwest monsoon (June to September) influences the coastal processes along the west coast of India and plays a significant role in creating variations in textural characteristics. The tides, waves, sea level changes, sediment supply rate, climatic and oceanographic settings and lithology have a profound impact on coastal sediments and morphodynamic conditions of the coast (Wang, 2012). Most coastal landforms along the east and west coast of India evolved during the late Quaternary Period. Statistical analysis helps in the identification of depositional environments and sedimentary processes that contribute to their formation. The grain size statistics can also be utilized to distinguish between high and moderate-energy environments (Nordstrom, 1977). The Pulmoddai Eastern Coast of Sri Lanka sediments are mostly fine-grained, moderately to moderately well sorted, negatively skewed to nearly symmetrical and mesokurtic (Wickramasooriya and Gunawardane, 2024). The moderate sorting indicates the accumulation of sediments with varying grain sizes from the reworking of beach ridges, alluvial activity and the annual occurrence of significant wave convergences (Mishra *et al.,* 2024). Various researchers have examined the textural characteristics of coastal sediments of the east and west coast of India (Kumar, 1977; Chaudhari *et al.,* 1981; Hanamgond *et al.,* 1999; Gawali *et al.,* 2020; Herlekar *et al.,* 2017). The fine to very fine sand, moderately sorted to moderately well sorted, strongly coarse skewed, and extremely platykurtic to leptokurtic beach sediments along Kelshi to Anjarle Creek in Ratnagiri District (Herlekar *et al.,* 2017). The textural investigation of surface sediments found that the inner shelf near Kalpakkam along the SE Indian coast is poorly sorted, positively

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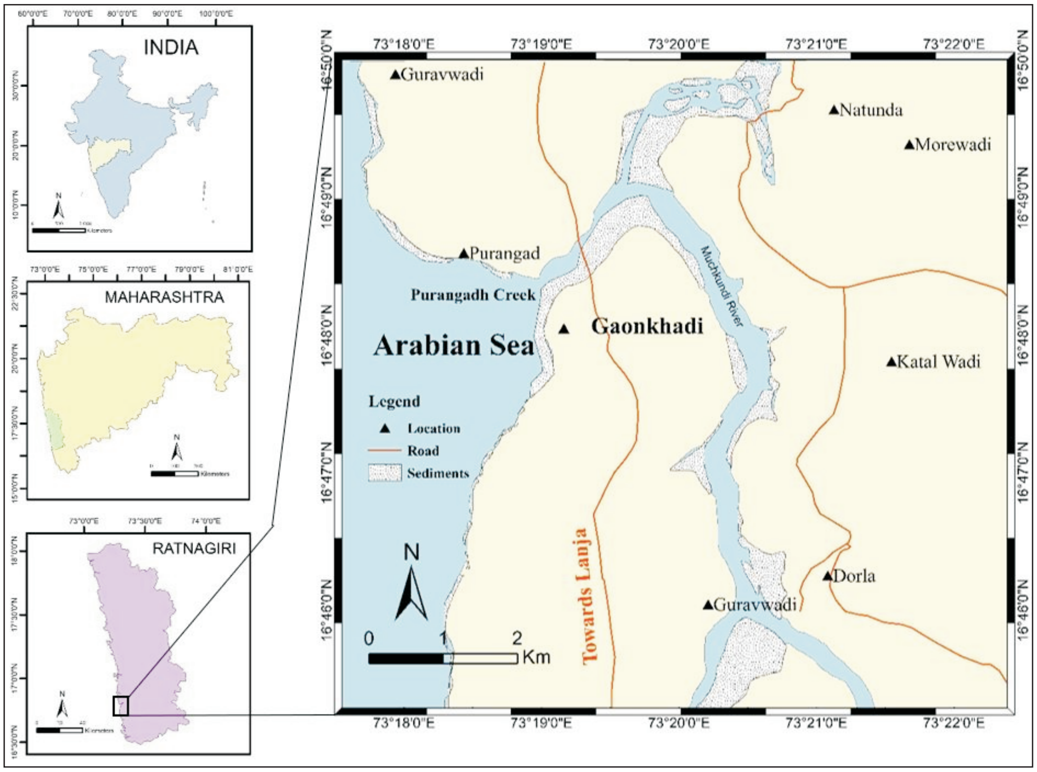

Fig.1. Location map of the study area

skewed sediments with extremely leptokurtic, very platykurtic properties (Selvaraj and Mohan, 2003). Shetty and Jayappa (2021) investigated sediment transport patterns and environmental changes along the Karnataka Coast. The remote sensing and GIS tools are used to monitor silt transport along Harwada Beach (Waghmare *et al.,* 2020). The mean size trend is decreasing from the Rameswaram to the Pradip coast during September at the backshore region while increasing trend from south to north during January at the foreshore region (Pradhan *et al.,* 2020). Textural analysis revealed fine to very fine size, well to very well sorted and predominantly mesokurtic to platykurtic distribution at Karwar Beach, India (Chavadi and Nayak, 1987). The objective of the present study is to investigate the seasonal variation in grain size, depositional environments, and the distribution of clay minerals in a tropical estuary. An insight into the distribution of major and trace elements in beach sediments along the Purangad to Gaonkhadi Coast is also being attempted in this study.

Study Area

The Purangad to Gaonkhadi Coast (Latitude, 16°48'27" N - 16°47'36" N and Longitude 73°18'38" - 73°18'58" E) is situated on the west coast of Maharashtra, Ratnagiri District, India and falls within Survey of India Toposheet No. 47H/5 (1:50,000) (Fig.1). The study area has a humid tropical climate, with an average rainfall of 2500-3000mm from June to September (Karlekar *et al.*, 2017). During the monsoon season, the waves along the South Konkan Coast exceed 4m in height, with a wave period of 3-6 seconds and a tidal current velocity of 70-90 cm/s (Karlekar *et al.*, 2017). The months of February to May start the summer season, and the maximum temperature ranges between 34°C to 40°C. The rainy season extends from June to September when the area receives substantial rainfall from the southwest monsoon. The months of October to January have pleasant climatic conditions and are considered as winter season. Various coastal geomorphological features are observed, such as sea cliffs, headlands, wave-cut platforms, and pocket beaches, as well as depositional features such as sand bars, sand spits, foredunes and raised beaches. The study area consists mainly of dendritic and rectangular drainage patterns. The Muchkundi River debouches into the Arabian Sea at the Gaonkhadi Coast. Geologically, the study area primarily comprised rock types such as Deccan Trap-Basalts, laterite, Late Quaternary and Holocene sediments (Herlekar and Sukhtankar, 2011).

Methodology

Sediment samples were collected from Purangad to Gaonkhadi Coast, Ratnagiri District, Maharashtra, India during pre-monsoon (PRM, February 2023) and post-monsoon (POM, November 2022) from four different sub-environments, foreshore, backshore, raised beach and foredune (Fig. 2). A total of 56 sediment samples (28 from each season) were collected for detailed grain size analysis (Fig.3). After the collection of sediments, samples were dried in a hot air oven at temperatures of about 60°C and their mass were reduced to 100gm by coning and quartering processes. These representative samples were treated with 1:10 HCl to remove carbonate shells and 30% H_2O_2 to remove any organic material (Ingram, 1970). These samples were then washed with distilled water and dried in a hot air oven at 60°C (Folk and Ward, 1957). Samples were weighed again after drying to determine the loss of carbonate and organic content. The samples were then sieved for 20 minutes on a Fritsch sieve shaker using ASTM sieves at half-phi intervals between mesh numbers 12 to 270. All sieved samples

Fig.2. Sample locations at a. foreshore; b. backshore; c. raised beach (berm); d. foredune; e. sandspit and f. Muchkundi River Mouth

were collected and weighed with the help of electronic weight balance. The graphic method has been used for the determination of statistical size parameters such as graphic mean size, graphic standard deviation, graphic skewness and graphic kurtosis from grain size data collected (Folk and Ward 1957), after sieving using software tools Gradistat 8.0 (Boltt and Pye, 2001). The depositional environments of the sediments were interpreted using linear discriminant functions (Sahu, 1964). GStat software was used to plot the CM plots and tractive current diagram established by Dinesh (2009), which is based on Passega (1957, 1964). Seven samples from the estuarine environment were powdered using an agate mortar pestle. The samples were subjected to X-ray diffraction (XRD) analysis. The powdered samples were examined by subjecting them to Cu-Kα X-ray radiation with a wavelength of 1.5418 Å, as assembled in an X-ray diffractometer (Rigaku, Ultima IV Version, Japan). Eight samples from foreshore and backshore environments were grind to a thin powder. Clay minerals in selected sediment sub-samples (<2μm) were determined following the procedure given by Rao and Rao (1995). The percentage of clay minerals was calculated by weighting the integrated peak area of basal reflection in the glycolated X-ray diffractograms by following the semi-quantitative method given by Biscaye (1965). Further, the samples were pressed into thin pellets and were subjected to X-ray fluorescence (XRF) studies to understand the elemental composition of materials.

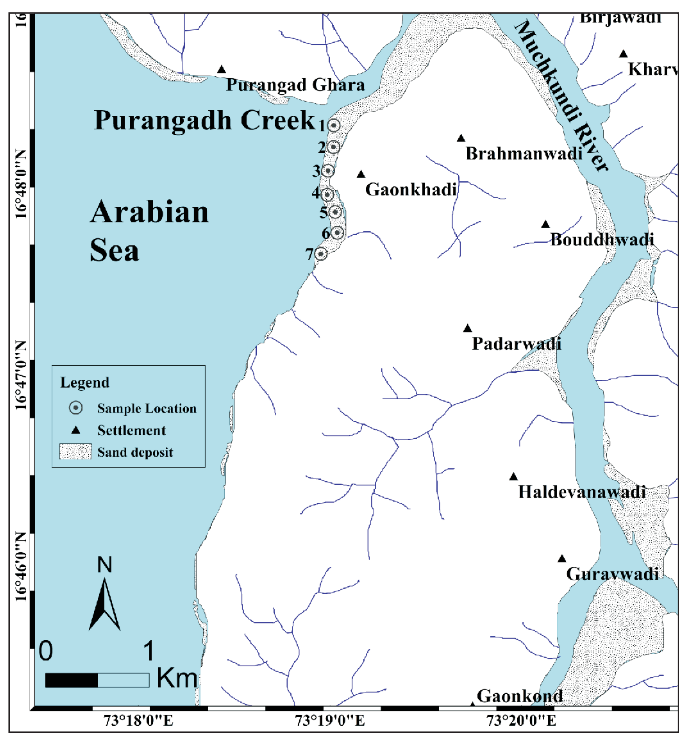

Fig.3. Sample location map of the study area

Results and Discussion

Frequency Distribution

During PRM season, foreshore, backshore and raised beach (Berm) sediments frequency distribution curve shows bimodal class. The foreshore, backshore and raised beach (Berm) sediments have the primary mode between 2 to 3 phi, whereas the secondary mode is between 3 to 4 phi (Fig.4 a,c,e). During POM season, the foreshore sediments frequency distribution curve shows unimodal to bimodal class. The foreshore sediments show the primary mode between 4 to 6 phi, whereas the secondary mode is between 6 to 7 phi scale. The backshore and raised beach (Berm) sediments frequency distribution curve shows a unimodal class with primary mode between 2.5 to 3.5 phi (Fig.4 b,d,f). The size frequency curves seem to indicate a transition from unimodal to bimodal class at places of river discharge along the Gaonkhadi Coast, due to intermixing of sediments of varied sizes.

Textural Characteristics

Grain size distribution is related to the physical forces responsible for the sediment mode of transport and depositional environment. Textural properties of sediments, such as mean size, standard deviation, skewness, and kurtosis, are often used to reconstruct the depositional environment.

Graphic Mean Size

The mean size of sediment signifies the source of sediment, transport and energy condition of different environments (Folk and Ward, 1957). The tidal wave energy of the transporting agent comprises the degree of turbulence as well as the involvement of longshore transport currents and waves. During PRM season, the foreshore sediments deposited are fine (2.49 phi) to medium sand (1.99 phi). The backshore, raised beach (Berm) and foredune sediments are fine sands. The foreshore sediments contain 85.72% medium sand and 14.28% fine sand. The backshore and raised beach sediments contain 100% fine sand, whereas foredune sediments show 85.72% fine-grained and 14.28% medium sand (Table 1-4).

During POM season, foreshore and backshore sediments deposited are coarse-grained sand, whereas raised beach (Berm) and foredune sediments are fine-grained sand. The foreshore and

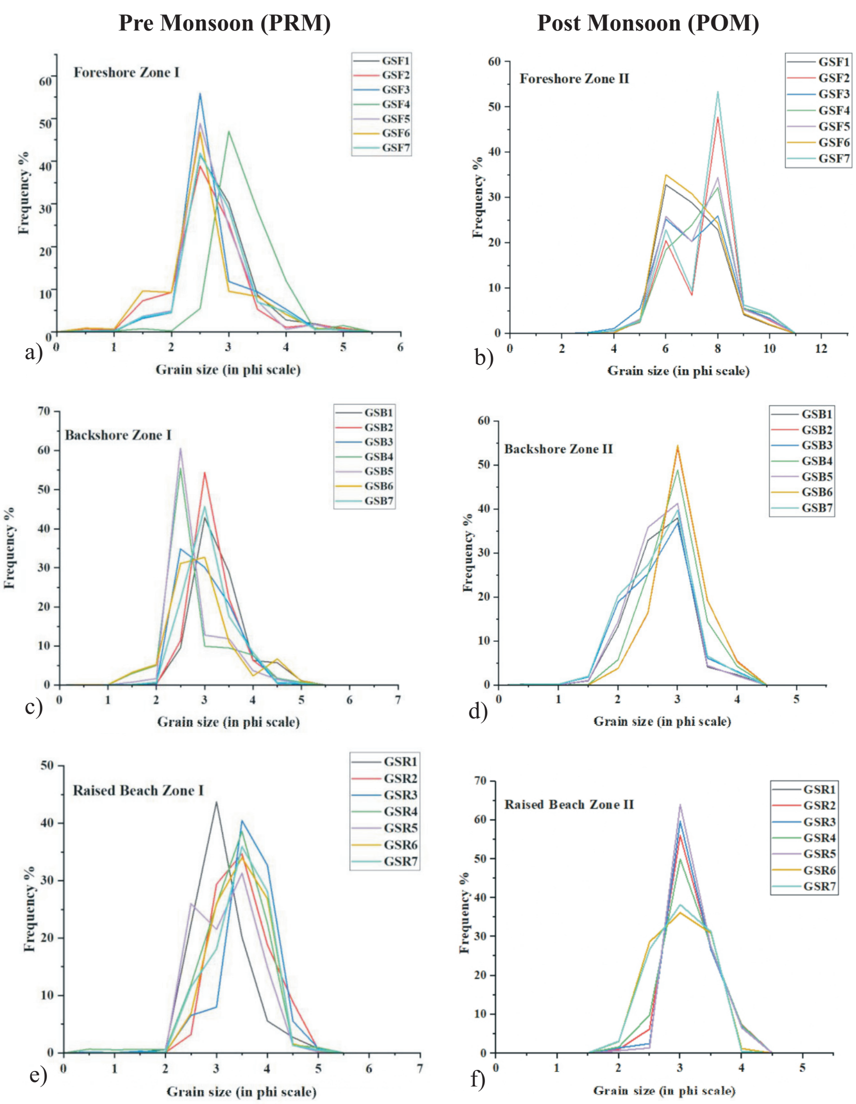

Fig.4. a,c,e. Grain-Size Frequency Curves of Pre-Monsoon season **;** b,d,f. Grain-Size Frequency Curves of Post-Monsoon season

Table 1: Graphic Measures from the grain size analysis

Sample No.	Mean PRM	Mean POM	Standard Deviation PRM	Standard Deviation POM	Skewness PRM	Skewness POM	Kurtosis PRM	Kurtosis POM	Inferences PRM	Inferences POM
a: Foreshore zone sediments of Pre-Monsoon (PRM) and PostMonsoon (POM)										
GSF1	1.99	0.65	0.52	2.41	0.13	-0.27	1.25	0.95	MG, MWS, FS, L	CG, VPS, CS, M
GSF2	1.85	0.45	0.58	1.47	-0.02	-0.37	1.35	0.91	MG, MWS, NS, L	CG, PS, SCS, M
GSF3	1.97	0.76	0.56	1.65	0.35	-0.55	1.50	1.21	MG, MWS, SFS, L	CG, PS, SCS, L
GSF4	2.49	0.49	0.45	1.32	0.23	-0.65	0.99	1.14	FG, WS, SFS, M	CG, PS, SCS, L
GSF5	1.93	0.36	0.47	1.50	0.14	-0.41	1.27	1.54	MG, WS, FS, L	CG, PS, SCS, VL
GSF6	1.79	0.59	0.68	1.74	0.08	-0.087	1.96	0.96	MG, MWS, NS, VL	CG, PS, NS, M
GSF7	1.98	0.48	0.52	1.69	0.14	-0.074	1.31	0.97	MG, MWS, FS, L	CG, PS, NS, M
b: Backshore zone sediments of Pre-Monsoon (PRM) and Post-Monsoon (POM)										
GSR1	2.30	2.47	0.52	0.87	0.17	-0.07	1.21	1.25	FG, MWS, FS, L	FG, MS, NS, L
GSR2	2.73	2.12	0.54	0.91	0.15	-0.25	0.90	0.96	FG, MWS, FS, P	FG, MS, CS, M
GSR3	2.90	2.41	0.49	1.02	-0.09	-0.32	1.16	1.17	FG, WS, NS, L	FG, PS, SCS, L
GSR4	2.61	2.54	0.55	1.32	-0.08	-0.17	0.95	0.97	FG, MWS, NS, M	FG, PS, CS, M
GSR5	2.43	2.25	0.58	0.78	-0.08	-0.21	0.79	1.38	FG, MWS, NS, P	FG, MS, CS, L
GSR6	2.69	2.12	0.51	0.81	-0.06	-0.25	0.83	1.54	FG, MWS, NS, P	FG, MS, CS, VL
GSR7	2.69	2.62	0.55	0.89	-0.12	-0.38	0.90	1.35	FG, MWS, CS, P	FG, MS, SCS, L
c: Raised beach zone sediments of Pre-Monsoon (PRM) and Post-Monsoon (POM)										
GSB1	2.47	0.47	0.51	1.47	0.24	-0.32	1.21	0.94	FG, MWS, FS, L	CG, PS, SCS, M
GSB2	2.39	0.72	0.44	1.32	0.25	-0.25	1.24	1.56	FG, WS, FS, L	CG, PS, CS, VL
GSB3	2.24	0.64	0.53	1.24	0.19	-0.36	0.87	1.57	FG, MWS, FS, P	CG, PS, SCS, VL
GSB4	2.04	0.85	0.62	1.51	0.43	-0.12	1.34	1.74	FG, MWS, SFS, L	CG, PS, CS, VL
GSB5	2.01	0.47	0.48	1.36	0.51	-0.17	1.11	1.43	FG, WS, SFS, M	CG, PS, CS, L
GSB6	2.15	0.51	0.68	0.85	0.18	-0.37	1.49	1.74	FG, MWS, FS, L	CG, MS, SCS, VL
GSB7	2.30	0.58	0.50	1.74	0.16	-0.45	1.23	1.35	FG, WS, FS, L	CG, PS, SCS, L
Dune zone sediments of Pre-Monsoon (PRM) and Post-Monsoon (POM)										
GSD1	2.78	2.63	0.55	0.74	0.13	-0.025	0.94	1.65	FG, MWS, FS, M	FG, MS, NS, VL
GSD2	2.43	2.22	0.44	0.52	0.24	-0.14	1.10	1.23	FG, WS, FS, M	FG, MWS, CS, L
GSD3	1.83	2.10	0.55	0.65	0.22	-0.18	2.52	1.78	MG, MWS, FS, VL	FG, MWS, CS, VL
GSD4	2.34	2.54	0.63	0.47	0.28	-0.19	0.84	1.54	FG, MWS, FS, P	FG, WS, CS, VL
GSD5	2.72	2.27	0.59	0.43	0.09	-0.12	0.93	1.27	FG, MWS, NS, M	FG, WS, CS, L
GSD6	2.39	2.44	0.61	0.58	0.14	-0.35	0.78	1.15	FG, MWS, FS, P	FG, MWS, SCS, L
GSD7	2.48	2.25	0.61	0.87	-0.03	-0.04	0.76	1.17	FG, MWS, NS, P	FG, MS, NS, L

backshore sediments contain 100% coarse-grained sand, whereas, raised beach (Berm) and foredune sediments show 100% fine sand. During the SW monsoon high hydrodynamic energy conditions prevail in the rivers and streams of the west coast of India with transport of coarser sediments in the foreshore and backshore region along the Gaonkhadi Coast.

Inclusive Graphic Standard Deviation

This parameter measures the sorting of sediment and indicates the fluctuations in the kinetic energy of the depositional agent (Folk and Ward, 1957). During PRM season, foreshore, backshore, raised beach (Berm) and foredune sediments are well sorted to moderately well sorted. The foreshore sediments are 71.43% moderately well-sorted and 28.57% well-sorted. The backshore, raised beach (Berm) and foredune sediments are moderately well sorted (85.72%) and well sorted (14.28%). The variations in the sorting values are due to the continuous addition of coarser and finer sediments in varying proportions. It reveals that the sorting character of coastal sediments is directly related to the landward part of the longshore currents which played a significant role in improving the sorting of the surficial sediments, where the majority of sediments were very well-sorted (Vasudevan *et al.,* 2024).

During POM season, the foreshore sediments become poorly sorted to very poorly sorted, while backshore and raised beach (Berm) sediments show moderately sorted to poorly sorted, whereas, foredune sediments show moderately well-sorted to well-sorted characteristics. The foreshore sediments are poorly sorted (85.72%) and very poorly sorted (14.28%). The backshore sediments are poorly sorted (85.72%) and moderately sorted (14.28%), whereas, raised beach sediments are moderately sorted (71.42%) and poorly sorted (28.58%). The foredune sediments are moderately well-sorted (42.84%) and moderately sorted to well-sorted (28.56%) (Table 1-4). The prevalence of poorly sorted sediments is due to the minimum distance of sediment transportation and the characteristics of such sediments mostly indicate their deposition in a shallow marine environment under the effect of a river (Kasim *et al.,* 2022). According to Griffiths (1951), the only sediments falling in the well-sorted category would be the fine and medium sands and most gravels, silt and clays would be poorly sorted to very poorly sorted.

Inclusive Graphic Skewness

During the PRM season, foreshore sediments show a symmetrical to strongly fine-skewed nature. The backshore sediments are fine skewed to strongly fine skewed. The raised beach (Berm) sediments show fine skewed to coarse skewed, whereas foredune sediments are mostly fine skewed to near symmetrical.

The foreshore sediments are fine-skewed (57.14%), near symmetrical (28.57%) and strongly fine-skewed (14.28%). Amongst the backshore and foredune sediments, 71.42% are finely-skewed and 28.58% are strongly fine skewed. The raised beach (Berm) sediments are near symmetrical (57.14%), fine skewed (28.57%) and coarse skewed (14.28%).

During the POM season, foreshore sediments show near symmetrical to strongly coarse skewed nature, while backshore sediments are coarse skewed to strongly coarse skewed. The raised beach (Berm) andforedune sediments are coarse skewed to near symmetrical. The foreshore sediments are strongly coarse skewed (57.14%), near symmetrical (28.57%) and coarse skewed sediments (14.28%). Amongst the backshore sediments, 57% are strongly coarse skewed and 43% coarse skewed. The raised beach sediments are coarsely skewed (57.12%), strongly coarse skewed (28.56%) and symmetrical (14.28%). Foredune sediments are coarse skewed (57.12%), symmetrical (28.56%) and strongly coarse sediments (14.28%) (Table 1-4). In the POM season, the percentage of negatively skewed sediments in the foreshore, backshore, raised beach and foredune are high, indicating the beach erosion due to the prevalence of high wave energy conditions.

Graphic Kurtosis

Kurtosis is the measure of the peakedness or flatness of sediments related to normal distribution. During the PRM season, foreshore sediments are mesokurtic to very leptokurtic. The backshore and raised beach (Berm) sediments show platykurtic to leptokurtic, while foredune sediments are platykurtic to very leptokurtic. The foreshore sediments are leptokurtic (71.42%), very leptokurtic (14.28%) and mesokurtic (14.28%). The backshore sediments are leptokurtic (71.42%) and platykurtic - mesokurtic (14.28%). The raised beach contains platykurtic (57.14%), leptokurtic (28.57%) and mesokurtic (14.28%) sediments. The foredune sediments are very leptokurtic (14.28%) and platykurtic - mesokurtic (42.85%). It is important to note that while the kurtosis values indicate a relatively peaked distributions, this does not imply a direct correlation with the sorting characteristics of the sediment population (Deshmukh, and Pophare, 2024).

During the POM season, the foreshore, backshore and raised beach (Berm) sediments range from mesokurtic to very leptokurtic. The foredune sediments are very leptokurtic to leptokurtic. The foreshore sediments are mesokurtic (57.12%), leptokurtic (28.56%) and very leptokurtic (14.28%). The backshore sediments are very leptokurtic (57.14%), leptokurtic (28.56%) and mesokurtic (14.28%). The raised beach contains leptokurtic (57.14%), mesokurtic (28.57%) and very leptokurtic (14.28%) sediments. The foredune sediments are leptokurtic (57.14%) and very leptokurtic (42.86%) (Table 1-4).

Bivariate Plots

Bivariate plots are used to understand the various depositional environments. Various scientists especially Friedman, (1967), Moiola and Weiser (1968), and Rajamanickam and Gujar (1984) have prepared discrimination boundaries to delineate different depositional environments of the sediments. Accordingly, various bivariate plots have been prepared to identify the depositional environment.

Graphic Mean Size vs. Graphic Standard Deviation

This bivariate plot (*after* Friedman, 1967) shows that during the PRM season, the majority of samples fall in the beach environment (Fig.5a) whereas, in the POM season the sediment samples indicate the riverine environment (Fig.5b).

Graphic Standard Deviation Vs Graphic Skewness

In the superimposed bivariate plots of graphic standard deviation *vs.* graphic skewness (Friedman, 1967) and (Moiola and Weiser, 1968) during the pre-monsoon season most of the samples indicate the beach environment (Fig. 5c), whereas very few samples suggest the riverine environment and for the post-monsoon season majority of the samples show the riverine environment (Fig. 5d).

Graphic Skewness vs. Graphic Kurtosis

The Graphic Skewness *vs.* Graphic Kurtosis (Friedman, 1967) shows that during the PRM season, 70% of the samples indicate a beach environment, whereas 30% of the samples show a riverine environment (Fig.5e). During the POM season 80% samples confirm beach environment, whereas 20% sample point riverine environment (Fig. 5f).

Graphic Mean Size vs. Graphic Skewness

The superimposed bivariate plots of graphic mean size *vs* graphic skewness (Moiola and Weiser, 1968) show that during the PRM season, 70% of the samples fall in an inland dune environment, whereas 30% of the samples exhibit a beach environment (Fig. 6a). However, in the POM season 100% samples suggest beach environment (Fig. 6b).

Graphic Mean Size vs. Graphic Standard Deviation

In the bivariate plots of graphic mean size *vs.* graphic standard deviation (Rajamanickam and Gujar, 1984), 60% of the samples fall in a beach environment and 40% of samples fall in a dune environment, during the PRM season (Fig. 6c). In POM season, 95% of the samples indicate beach environment, whereas 5% sample show dune environment (Fig. 6d).

Linear Discriminant Analysis (LDA)

LDA is used to decipher the variations of energy that seem to have a strong correlation with different processes and depositional environments (Sahu, 1964). This helps in the correlation of various deposition processes. The following formulas and their associations with specific environments were used to interpret the environment of sediment deposition, aeolian or beach.

Y_1 Aeolian: Beach =

$$- 3.5688\ M + 3.7016\ r^2 - 2.0766\ SK + 3.1135\ KG \qquad (1)$$

Where if Y_1 is > -2.7411 then the environment of deposition is beach, and if Y_1 is <-2.7411 the environment of deposition is considered aeolian.

Further, to delineate and to confirm the environment of deposition between beach and shallow marine, the following equation has been applied:

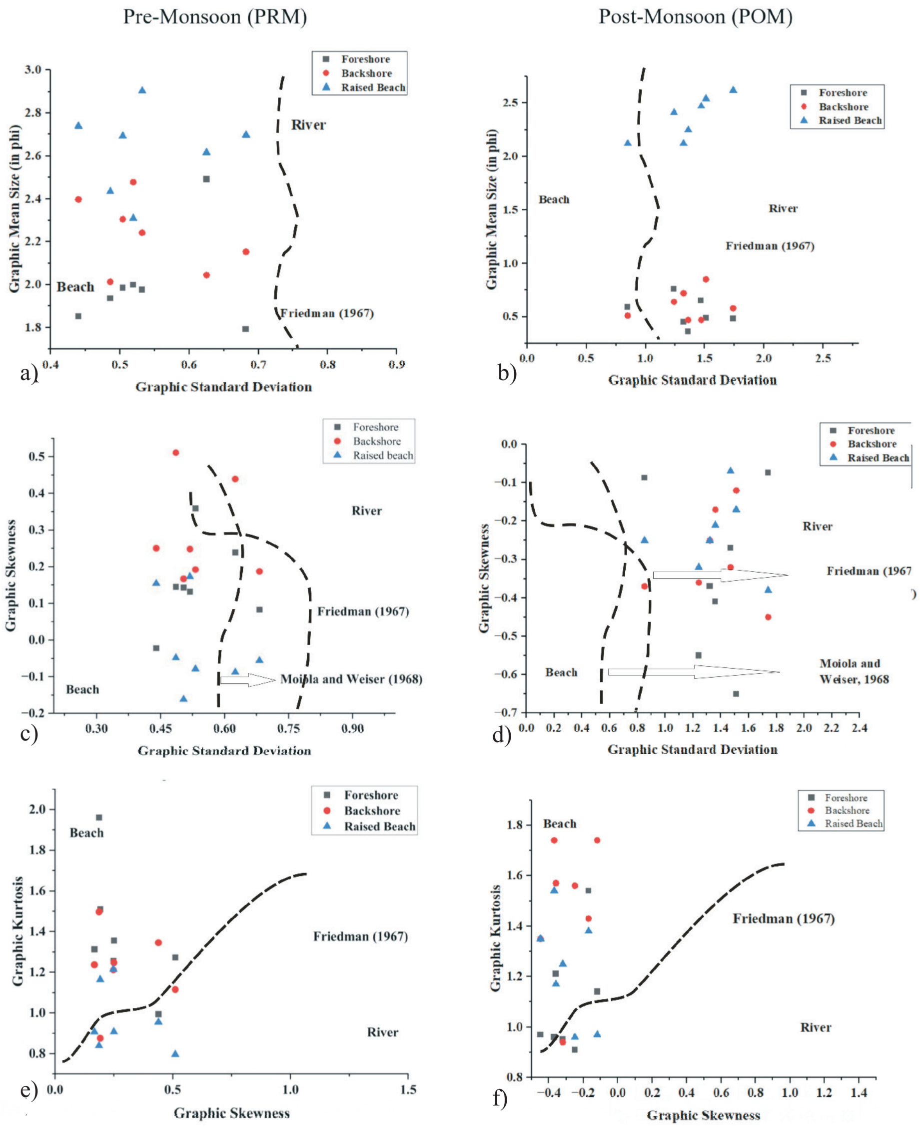

Fig.5. Bivariate plots of statistical size parameters for environment discrimination, a) Graphic Mean Size *vs.* Graphic Standard deviation (PRM); b) Graphic Mean Size *vs.* Graphic Standard deviation (POM); c) Graphic Standard deviation *vs.* Graphic skewness (PRM); d) Graphic Standard deviation *vs.* Graphic skewness (POM); e) Graphic skewness *vs.* Graphic kurtosis (PRM); f) Graphic skewness *vs.* Graphic kurtosis (POM)

Y_2 Beach: Shallow marine =

$15.6534\ M + 65.7091\ r^2 + 18.1071\ SK + 18.5043\ KG$ (2)

Where if Y_2 is <63.3650, the environment of deposition is shallow marine, and if Y_2 is >63.3650, the environment of deposition is a beach

To distinguish the environment of deposition between shallow marine and fluvial, the following equation has been applied:

Y_3 Shallow marine: Fluvial =

$0.2852\ M - 8.7604\ r^2 - 4.8932\ SK + 0.0428\ KG$ (3)

Where if Y_3 is > -7.4190 environment of deposition is shallow marine, and if Y_3 is <-7.4190, the environment of deposition is fluvial.

(M= Mean, r = Standard Deviation, SK = Skewness and KG= Kurtosis)

Linear discriminant functions (LDF) are calculated using the formula given above for the PRM and POM. During the PRM season, the LDF plots of Y1 *vs* Y2, 92% of sediments suggest an aeolian/shallow agitated environment, while 8% of sediments indicate a beach shallow environment. During POM, plots of Y1 *vs* Y2 100% sediments disclosed a shallow beach environment (Fig. 7a and 5b). In the PRM and POM seasons, plots of Y2 *vs* Y3 100% sediments indicate a shallow marine agitated environment (Fig.7c-d). During PRM, Y1 values (foreshore sediments) in 86% of the samples show a beach environment and 14% of samples indicate an aeolian environment. The backshore sediments Y1 values 71% of the samples suggest a prevalence of aeolian process and 29% sediment point beach environment, while 100% of the samples from the raised beach and foredune indicate aeolian processes. Concerning the Y2 and Y3 values (foreshore, backshore, raised beach and foredune) 100% of the samples suggest a shallow marine environment. Furthermore, the Y4 values (foreshore) show the involvement of the turbidity process in the formation of 71% of the samples and 29% of samples show fluvial conditions. Similarly, backshore sediment samples (71%) indicate a fluvial environment and 29% of samples show a turbid environment (Table 2a-d).

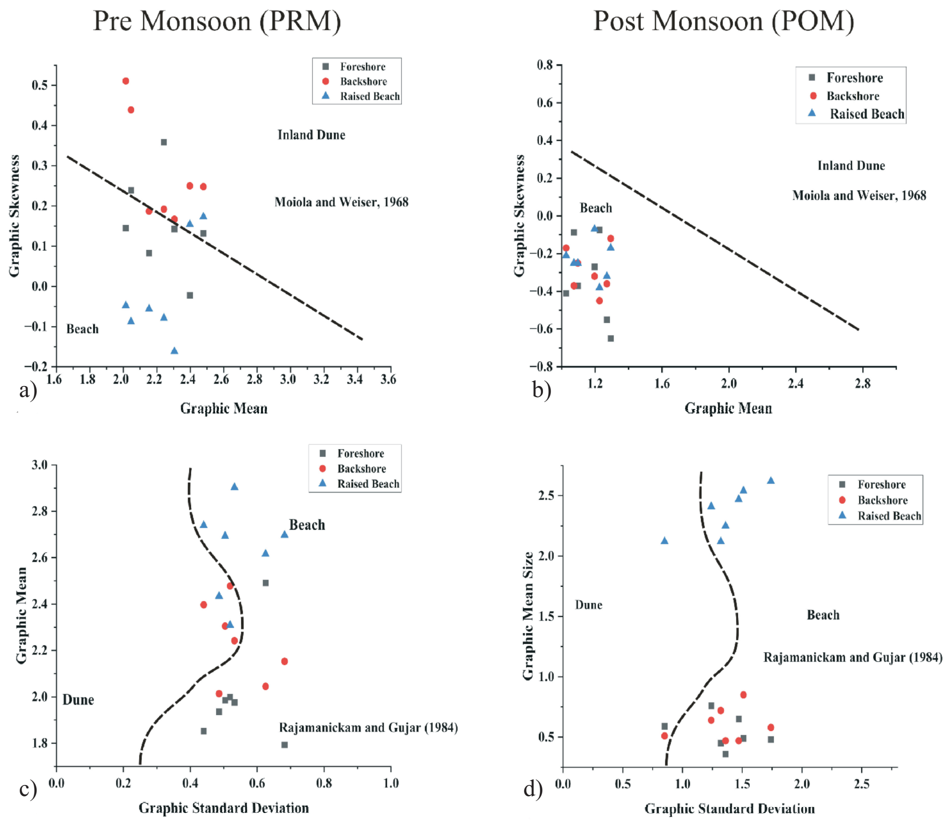

Fig.6. Bivariate plots showing the textural patterns of sediments in terms of statistical parameters, a) GraphicMean size *vs.* Graphic skewness (PRM); b) Graphic Mean size *vs.* Graphic skewness (POM); c) Graphic Mean size *vs.* Graphic Standard deviation (PRM); d) Graphic Mean size *vs.* Graphic Standard deviation (POM)

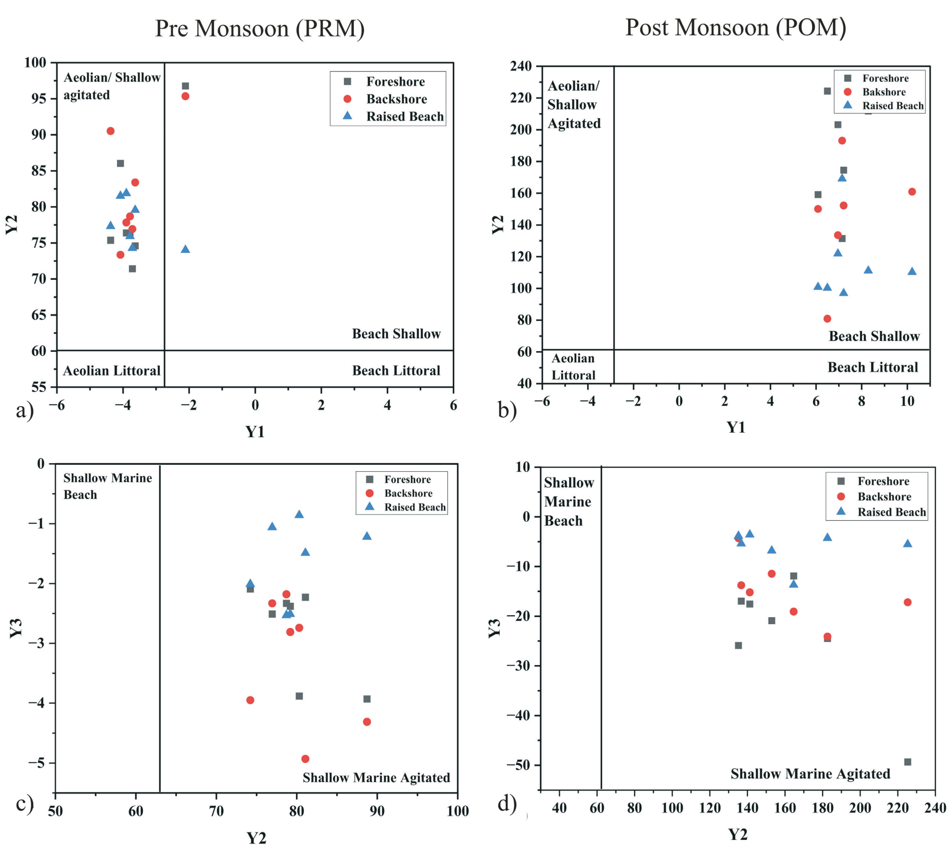

Fig.7. a, c. Linear Discriminant Analysis Plots Y1 vs. Y2 and Y2 vs. Y3 of Pre-Monsoon season; b, d. Linear Discriminant Analysis Plots Y1 vs. Y2 and Y2 vs. Y3 of Post-monsoon season

Table 2: Linear Discriminant Analysis (LDA) - Pre-Monsoon

Sample No.	Y1	Y2	Y3	Y4
a: Foreshore (PRM)				
GSF1	-2.50 (Beach)	74.60 (Shallow marine)	-2.38 (Shallow marine)	9.183 (Turbidity)
GSF2	-1.062 (Beach)	76.40 (Shallow marine)	-2.33 (Shallow marine)	8.602 (Turbidity)
GSF3	-1.934 (Beach)	86.03 (Shallow marine)	-3.88 (Shallow marine)	12.05 (Turbidity)
GSF4	-5.521 (Aeolian)	75.38 (Shallow marine)	-2.23 (Shallow marine)	8.850 (Turbidity)
GSF5	-2.404 (Beach)	71.43 (Shallow marine)	-2.09 (Shallow marine)	9.30 (Turbidity)
GSF6	1.276 (Beach)	96.77 (Shallow marine)	-3.93 (Shallow marine)	12.51 (Turbidity)
GSF7	-2.268 (Beach)	76.22 (Shallow marine)	-2.51 (Shallow marine)	9.56 (Turbidity)
b: Backshore Zone (PRM)				
GSB1	-4.59 (Aeolian)	83.39 (Shallow marine)	-2.81 (Shallow marine)	10.08 (Fluvial)
GSB2	-4.47 (Aeolian)	77.84 (Shallow marine)	-2.18 (Shallow marine)	10.19 (Fluvial)
GSB3	-4.63 (Aeolian)	73.36 (Shallow marine)	-2.74 (Shallow marine)	7.756 (Turbidity)
GSB4	-2.58 (Aeolian)	90.52 (Shallow marine)	-4.93 (Shallow marine)	11.80 (Fluvial)
GSB5	-3.90 (Aeolian)	76.93 (Shallow marine)	-3.95 (Shallow marine)	10.99 (Fluvial)
GSB6	-1.69 (Aeolian)	95.35 (Shallow marine)	-4.31 (Shallow marine)	11.01 (Fluvial)
GSB7	-3.78 (Aeolian)	78.68 (Shallow marine)	-2.33 (Shallow marine)	9.537 (Turbidity)
c: Raised Beach (PRM)				
GSR1	-3.81 (Aeolian)	79.57 (Shallow marine)	-2.51 (Shallow marine)	9.46 (Turbidity)
GSR2	-6.17 (Aeolian)	81.89 (Shallow marine)	-2.53 (Shallow marine)	8.03 (Turbidity)
GSR3	-5.67 (Aeolian)	81.52 (Shallow marine)	-0.86 (Shallow marine)	7.92 (Turbidity)
GSR4	-5.03 (Aeolian)	77.32 (Shallow marine)	-1.49 (Shallow marine)	6.57 (Turbidity)
GSR5	-4.85 (Aeolian)	74.29 (Shallow marine)	-2.01 (Shallow marine)	5.88 (Turbidity)
GSR6	-5.92 (Aeolian)	74.02 (Shallow marine)	-1.22 (Shallow marine)	6.21 (Turbidity)
GSR7	-5.32 (Aeolian)	75.93 (Shallow marine)	-1.06 (Shallow marine)	5.87 (Turbidity)
d: Foredune (PRM)				
GSD1	-6.11 (Aeolian)	83.72 (Shallow marine)	-2.50 (Shallow marine)	8.13 (Turbidity)
GSD2	-4.99 (Aeolian)	76.26 (Shallow marine)	-2.19 (Shallow marine)	9.42 (Turbidity)
GSD3	1.985 (Aeolian)	99.97 (Shallow marine)	-3.19 (Shallow marine)	16.45 (Turbidity)
GSD4	-4.82 (Aeolian)	84.31 (Shallow marine)	-4.25 (Shallow marine)	8.369 (Turbidity)
GSD5	-5.71 (Aeolian)	84.52 (Shallow marine)	-2.69 (Shallow marine)	7.790 (Turbidity)
GSD6	-4.99 (Aeolian)	79.59 (Shallow marine)	-3.29 (Shallow marine)	7.091 (Turbidity)
GSD7	-5.05 (Aeolian)	77.52 (Shallow marine)	-2.49 (Shallow marine)	6.015 (Turbidity)

During POM, Y1 values (Foreshore, backshore and raised beach) in 100% of the sediment samples indicate a beach environment, while Y2 values (Foreshore, backshore and raised beach and foredune) in 100% of the sediments show a shallow marine environment. As far as Y3 is concerned, 100% of the samples from foreshore and foredune sediments indicate a fluvial environment. Furthermore, Y4 values (Foreshore, backshore and raised beach and foredune) 100% sediment samples indicate a turbid environment. The results show that the majority of the sediments are deposited in a shallow marine environment by river, beach and aeolian processes indicated by a nearshore eddy with water turbidity (Table 3a-d).

C-M Plots

C-M plots can be helpful in understanding the sources and transportation of sediment movement in various environments. They are plotted as coarsest one percentile of grain size (C) against the median grain size (M) of the sediment and it is plotted on double log paper (Passega, 1957). It is divided into five classes, namely NO (rolling), OP (bottom suspension and rolling), PQ (graded suspension no rolling), QR (uniform suspension), and RS (pelagic suspension). The grain size distribution depends on sedimentary processes especially the first percentile (C) which characteristics the highest capability of hydrodynamical transport and the median (M) represents the mean transport capacity of hydrodynamical factors.

During the PRM and POM seasons, CM plots depict sources of sediments mostly by the beach and tractive currents (Fig.8a-b). The prime factors for the transportation of beach sediments are mainly bottom suspension and rolling conditions. The sediments are segregated into fine and coarse grain sizes during pre and post-monsoon seasons respectively. PQ represents coarse grains sediments transported by rolling. The sediments are set by bottom suspension and deposited by rolling. As a result, the sediment was deposited as a rolling and suspension mechanism process. During PRM and POM, the mode of sediment transport is mainly bottom suspension and rolling and graded suspension with no rolling (Fig. 8c-d).

Geochemistry

The X-ray Fluorescence (XRF) study results reveals the presence of Si, Al, Fe, Mg, Ca, K, Sr, Mn, P, Na, S, Cl, Ti, V, Cr, Zr, and Ba. The concentration of all these 17 elements is variable if we compare foreshore and backshore microenvironments from all the selected stations. As far as major elements are concerned; their concentration in the foreshore region showed Fe>Si>Al>Ca>Ti>Mg>Na, and in the backshore, showed a concentration of Fe>Si>Ti>Al>Ca>Mg>Na, respectively. The trend in trace elemental composition in the foreshore zone showed Cl>K>Mn>S>P>V>Zr>Cr>Sr>Ba whereas, the backshore zone indicates Mn>Cl>K>V>P>S>Zr>Cr>Ba>Sr.

The high concentration of 'Fe' has been observed in the

Table 3: Linear Discriminant Analysis (LDA) - Post-Monsoon

Sample No.	Y1		Y2		Y3		Y4	
a: Foreshore (POM)								
GSF1	22.70	(Beach)	404.50	(Shallow marine)	-49.33	(Fluvial)	1.339	(Turbidity)
GSF2	9.994	(Beach)	159.17	(Shallow marine)	-16.95	(Fluvial)	1.777	(Turbidity)
GSF3	12.27	(Beach)	203.22	(Shallow marine)	-20.89	(Fluvial)	2.153	(Turbidity)
GSF4	9.600	(Beach)	131.49	(Shallow marine)	-11.89	(Fluvial)	1.309	(Turbidity)
GSF5	12.69	(Beach)	174.55	(Shallow marine)	-17.54	(Fluvial)	4.743	(Turbidity)
GSF6	12.27	(Beach)	224.36	(Shallow marine)	-25.89	(Fluvial)	3.701	(Turbidity)
GSF7	12.03	(Beach)	211.79	(Shallow marine)	-24.48	(Fluvial)	3.831	(Turbidity)
b: Backshore Zone (POM)								
GSB1	9.913	(Beach)	160.95	(Shallow marine)	-17.19	(Fluvial)	2.289	(Turbidity)
GSB2	9.256	(Beach)	150.10	(Shallow marine)	-13.77	(Fluvial)	6.391	(Turbidity)
GSB3	9.043	(Beach)	133.59	(Shallow marine)	-11.46	(Fluvial)	5.728	(Turbidity)
GSB4	11.07	(Beach)	193.15	(Shallow marine)	-19.07	(Fluvial)	8.096	(Turbidity)
GSB5	9.974	(Beach)	152.28	(Shallow marine)	-15.18	(Fluvial)	6.018	(Turbidity)
GSB6	7.040	(Beach)	80.956	(Shallow marine)	-4.299	(Shallow marine)	6.795	(Turbidity)
GSB7	14.27	(Beach)	224.85	(Shallow marine)	-24.09	(Fluvial)	3.314	(Turbidity)
c: Raised-Beach (POM)								
GSR1	-1.98	(Beach)	110.26	(Shallow marine)	-5.530	(Shallow marine)	7.622	(Turbidity)
GSR2	-0.99	(Beach)	100.84	(Shallow marine)	-5.385	(Shallow marine)	4.594	(Turbidity)
GSR3	-0.44	(Beach)	121.94	(Shallow marine)	-6.811	(Shallow marine)	5.358	(Turbidity)
GSR4	0.758	(Beach)	169.12	(Shallow marine)	-13.67	(Fluvial)	5.119	(Turbidity)
GSR5	-1.04	(Beach)	96.931	(Shallow marine)	-3.601	(Shallow marine)	7.269	(Turbidity)
GSR6	0.177	(Beach)	100.27	(Shallow marine)	-3.854	(Shallow marine)	7.733	(Turbidity)
GSR7	-1.43	(Beach)	111.16	(Shallow marine)	-4.275	(Shallow marine)	6.158	(Turbidity)
d: Foredune (POM)								
GSD1	-2.17	(Beach)	107.23	(Shallow marine)	-3.854	(Fluvial)	10.24151	(Fluvial)
GSD2	-2.80	(Aeolian)	72.744	(Shallow marine)	-0.998	(Fluvial)	7.060272	(Turbidity)
GSD3	-0.01	(Aeolian)	90.313	(Shallow marine)	-2.146	(Fluvial)	9.554093	(Turbidity)
GSD4	-3.06	(Beach)	79.331	(Shallow marine)	-0.215	(Fluvial)	8.615227	(Turbidity)
GSD5	-3.21	(Beach)	69.010	(Shallow marine)	-0.331	(Fluvial)	7.477155	(Turbidity)
GSD6	-3.15	(Beach)	75.241	(Shallow marine)	-0.489	(Fluvial)	5.355226	(Turbidity)
GSD7	-1.50	(Aeolian)	105.88	(Shallow marine)	-5.743	(Fluvial)	7.241515	(Turbidity)

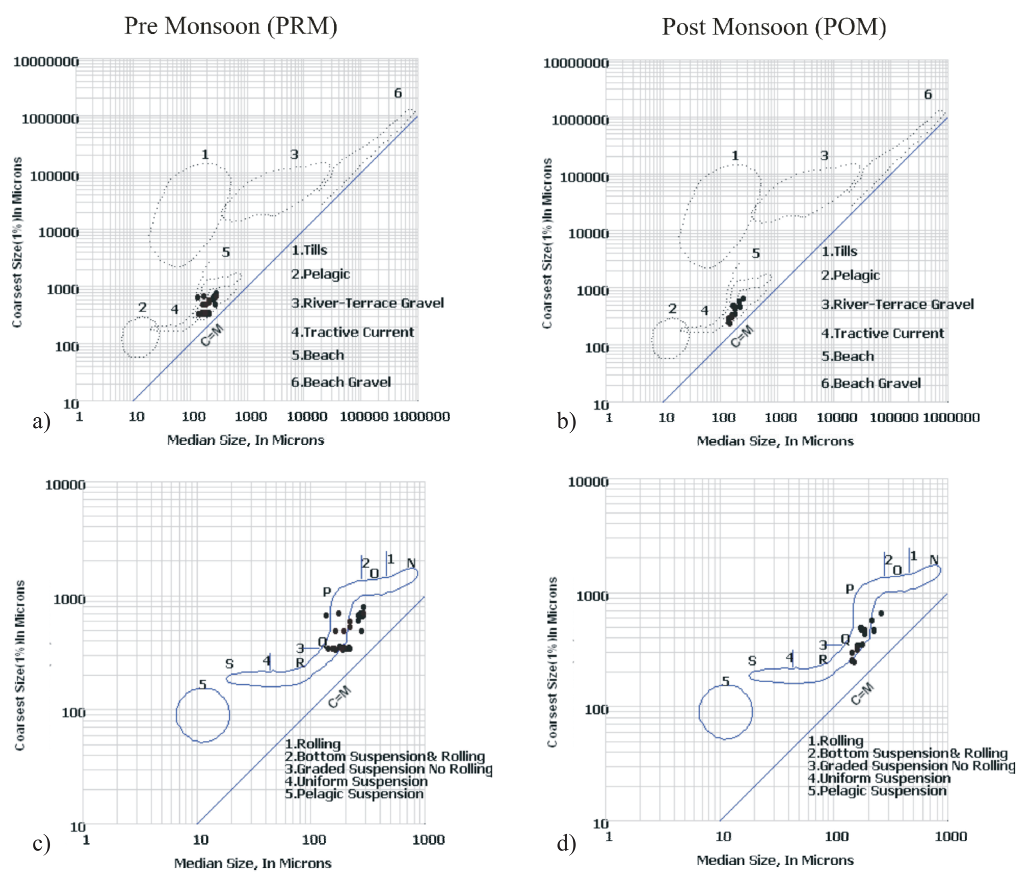

Fig.8. a, c. CM Plot and Tractive Current diagram of Pre-Monsoon season; b, d. CM Plot and Tractive Current diagram of Post-Monsoon season

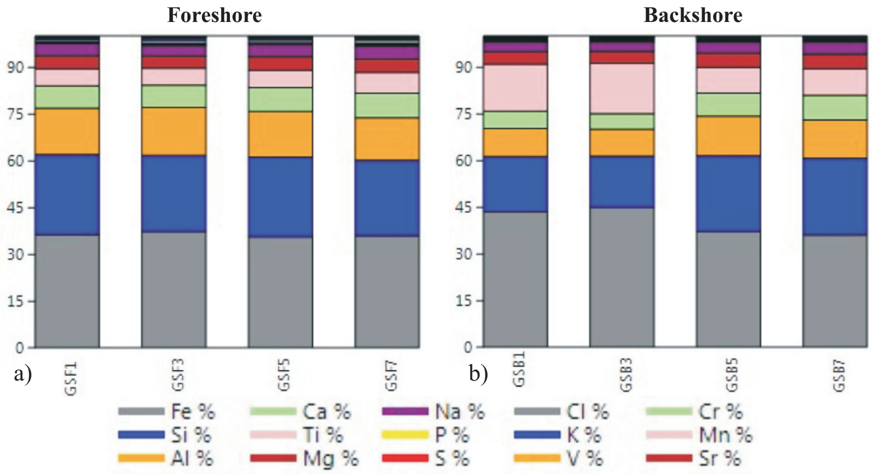

Fig.9. Major and trace elements of foreshore and backshore sediments

northern part while it decreases towards the south along the beach. 'Fe' and 'Ti' concentrations also increase cross shore from foreshore to backshore, while Si, Al, and Ca concentration decreases from foreshore to backshore. The foreshore zone concentration of major elements from 'Fe' to 'Na' exhibits a gradually decreasing nature from Northern to Southern locations whereas the backshore zone exhibits a more or less abrupt trend from 'Fe' to 'Al' and a significant concentration of 'Ti' is also observed in backshore zone compared to foreshore zone (Fig.9a). 'Fe' concentration is high at backshore zone than the foreshore zone and 'Si' concentration is significant within the foreshore zone as compared to backshore zone (Fig. 9b). The percent concentration of 'Al' and 'Ca' are higher within the foreshore zone than the backshore zone. More or less the same concentrations of 'Mg' and 'Na' were observed within both foreshore and backshore zones. Trace element concentrations within both zones exhibit no significant variations. The changing pattern of geochemical signatures exhibits different rates of erosion and deposition, which seems to be tied to the monsoonal precipitation within the area (Gawali *et al.,* 2021).

Mineralogical Analysis

In the mudflat sediments, clay, a fine-grained natural material, consists of clay minerals that are sensitive to the changes in geological processes or sedimentary environment reflect source and climatic characteristics of an area (Lan *et al.,* 2012). Mudflats primarily consist of fine sediments (silt and clay) and are influenced by tides, waves and fluvial processes (Lesueur *et al.,* 2003). X-ray diffraction studies of the mud flat samples have indicated the presence of kaolinite, illite, smectite, and chlorite. The concentration of kaolinite and illite is higher than smectite and chlorite. The clay minerals are generally formed by the weathering of rocks, and their type depends on the parent rock and the climatic conditions (Parthasarathy, 2003). The primary product of geochemical weathering of the basalts under slow drainage conditions initially gives rise to Kaolinite, especially in Mg^{++}, Fe^{++}, Ca^{++}, Na^{++} metal ions, Al^{++}, and $SiO4^{+}$. Thus, the intense weathering of Deccan trap basalts in humid tropical climatic conditions could possibly have released smectite. The presence of high smectite in the inner continental shelf off Ratnagiri-Goa along the continental margins of India is attributed to a basaltic source (Rao and Rao, 1995). The weathering of laterite covers present over the Deccan Trap Basalts releasing kaolinite. Kaolinite, illite, and chlorite therefore appear to have formed in the hinterland and were transported in suspension through streams and rivers and finally meeting the Arabian sea. Nasnodkar and Nayak (2019) reported the kaolinite,

Table 4: The percentage of Major and trace elements of foreshore and backshore sediments

Sr. No.	Symbol	Element	Foreshore Stations				Backshore Stations			
			GSF1 %	GSF3 %	GSF5 %	GSF7 %	GSB1 %	GSB3 %	GSB5 %	GSB7 %
1	Fe	Iron	36.24	37.29	35.59	35.92	43.39	44.81	37.09	36.05
2	Si	Silicon	25.66	24.38	25.48	24.09	17.76	16.47	24.34	24.54
3	Al	Aluminium	14.76	15.29	14.67	13.69	8.99	8.549	12.71	12.2
4	Ca	Calcium	7.203	7.133	7.536	7.758	5.495	5.03	7.386	7.979
5	Ti	Titanium	5.412	5.482	5.594	6.735	15.06	16.12	8.174	8.484
6	Mg	Magnesium	4.243	3.754	4.246	4.169	4.015	3.865	4.564	4.737
7	Na	Sodium	3.77	3.47	4.05	4.35	3.01	2.99	3.58	3.82
8	P	Phosphorous	0.278	0.265	0.276	0.245	0.163	0.148	0.253	0.239
9	S	Sulphur	0.192	0.276	0.202	0.42	0.087	0.075	0.095	0.11
10	Cl	Chlorine	0.786	1.171	0.923	1.19	0.443	0.405	0.387	0.38
11	K	Potassium	0.606	0.63	0.596	0.559	0.273	0.244	0.481	0.5
12	V	Vanadium	0.123	0.129	0.126	0.159	0.333	0.352	0.178	0.182
13	Cr	Chromium	0.041	0.041	0.042	0.038	0.042	0.038	0.04	0.038
14	Mn	Manganese	0.345	0.345	0.352	0.374	0.518	0.541	0.404	0.407
15	Sr	Strontium	0.036	0.045	0.037	0.038	0.014	0.012	0.026	0.026
16	Zr	Zirconium	0.047	0.052	0.047	0.047	0.053	0.053	0.047	0.05
17	Ba	Barium	0.019	0.022	0.027	0.019	0.067	0.019	0.023	0.023

smectite, illite and chlorite in mudflat core sediments in the Vaghotan Estuary.

Discussion

The variation in grain sizes for the PRM to POM seasons was the result of changes in wave activity occurring along the Gaonkhadi Coast. The unimodal and bimodal nature of frequency curves indicates a mixed nature of sediments derived from beach and river sediments. Sediment grain size exhibits an increasing trend from the PRM to POM periods. The presence of coarse sediments on the foreshore and backshore during the POM was due to the prevailing high wave energy condition. The foreshore zone experiences highly dynamic sedimentary processes in the Gaonkhadi Coast. The fine and coarse sediments are indicative of the energy condition of the beach environment, whereas a positive skewness implies a depositional environment and negative skewness indicates erosion in a high-energy environment (Duane, 1969).

During the PRM season, foreshore, backshore, raised beach and foredune sediments are well sorted- moderately well sorted. During the POM, foreshore sediments are poorly sorted to very poorly sorted, while backshore and raised beach sediments are moderately- poorly sorted. Along the Muchkundi River mouth, poorly sorted sediments are prevalent in Gaonkhadi Beach. It indicates the mixing of terrigenous coarser or finer sediments, regularly brought by the Muchkundi River. The skewness of foreshore sediments of the PRM season is symmetrical to strongly fine skewed, while backshore sediments are fine skewed to strongly fine skewed. This is possible only in the absence of extreme conditions like tidal variations, wave breaking and seasonal supply of detrital sediments (Rajamanickam and Gujar, 1997).

Conclusions

The Gaonkhadi Beach, Ratnagiri District, has been interpreted based on grain size analysis, frequency distribution curves, LDF, and CM plots. During the PRM season, sediments are represented by mostly the fine-grained to medium-grained sand indicating moderate energy conditions, moderately well to well-sorting, mostly fine-skewed to symmetrical, platykurtic to very leptokurtic, whereas during the POM season the sediments are mostly coarse-grained indicating high hydrodynamic energy condition during south-west monsoon. These sediments are poorly sorted to very poorly sorted, negatively skewed and mesokurtic to leptokurtic. The CM plots indicate sediments mostly originated in the tractive current and beach environment in both the seasons. **T**he mud flat samples have indicated the presence of kaolinite, illite, smectite, and chlorite. The concentrations of kaolinite and illite were higher than the smectite and chlorite from north to south in the study area.

Authors' Contributions

PPB: Formal Analysis, Data Curation, Methodology, Software, Validation. **MAH**: Investigation, Conceptualization, Supervision, Writing Original Draft, Visualization, Reviewing and Editing. **PBK**: Data Curation, Reviewing, Methodology, Software. **OP:** Formal Analysis, Methodology, and Software.

Conflict of interest

The Authors declare no conflict of interest.

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