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Sediment Texture and Geochemistry of Beaches between Redi-Vengurla, Sindhudurg, West Coast of India

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ABSTRACT

Hanamgond, P.T.; Gawali, P.B.; Lakshmi, B.V.; Mahesh Babu, J.L.V., and Deendayalan, K., 0000. Sediment texture and geochemistry of beaches between Redi-Vengurla, Sindhudurg, west coast of India. *Journal of Coastal Research,* 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Textural and geochemical determinations were carried out on three beaches (Vengurla, Aravali, and Redi) of the Sindhudurg district, Maharashtra, west coast of India. Seasonal sediments from the beach were collected during 2003–04 to understand the sediment dynamics (texture, dispersal pattern, depositional environment, *etc.*) and geochemical characteristics. In general, a seaward grain size fining is seen along Vengurla beach (swash-backwash phenomenon), with a coarsening seaward trend along Aravali and Redi beaches (high-energy conditions). The CM pattern studies reveal traction currents as the transport mechanism. Thus, the sediments of the study area are deposited under moderate to high-energy conditions. The geochemical study shows that the percentages of V, Cr, and Zr are greater in premonsoon; Si, Al, K, Sr, Mn, Ti, and P are greater in monsoon; and Mg, Ca, K, Mn, Na, S, Cl, and P are greater in postmonsoon at Vengurla beach. At Aravali beach, the percentages of Si and Al are more than those observed at Vengurla or Redi beaches. The percentages of Mn, Na, S, and Cl are greater premonsoon; Si, Al, Fe, K, Ti, Cr, and Zr are greater in monsoon compared with the other two seasons; and Mg, Ca, Sr, Mn, P, and V are greater in postmonsoon. At Redi, Cr and Ca are greater than at the two other beaches. Percentage of Fe is greater in all the seasons at Redi. Mn and Ti are quantitatively greater in premonsoon; Si, Al, Fe, and K are greater in monsoon; and Fe, Mg, Ca, Sr, Na, S, Cl, P, V, Cr, and Zr are greater in postmonsoon. These seasonal changes can be attributed to changing wind, wave, and current regimes prevalent in this coastal tract, which seem to be dissimilar even though the three beaches are adjacent (but separated by headlands or a creek).

ADDITIONAL INDEX WORDS: *Sediment dynamics, Maharashtra.*

INTRODUCTION

Beaches are nonstatic and ever-changing landscapes formed by complex interactions involving sediment source, wave and wind energy, river discharge, precipitation intensity, and ambient geomorphology. The beaches are sensitive to changing climatic and environmental conditions involving variation in atmospheric pressures and subsequently generated winds (Simm, 1996). These changes also influence the effect that waves, tides, and currents have on the morphology of beaches, not least the sea level, which is one of the most important components of shoreline position change (Leatherman 2001).

Mineralogical and geochemical characteristics of beach sands are closely related to geology and hydrodynamics. Analysis of such sediments for their compositional makeup can provide valuable insight into the local and regional hydrodynamics, patterns of sediment dispersal/transport, distribution, and source. Beaches are sensitive to erosive and accretionary processes, and these changes can be easily quantified by morphological changes it undergoes within a span of weeks, months, or years. Since many recreational facilities line this coastal transect all over the world, any deleterious change effected on a beach has economic and societal effects that need to be addressed and prioritized. Beaches and their adjacent nearshore zones act as buffers to wave energy. Consequently, they are sensitive to change over timescales ranging from a few seconds to several years. The study of beach changes assists in forecasting coastal erosion and deposition, among other things. Wind, waves, and longshore currents are the driving force behind coastal erosion, wherein valuable property frequently is lost to the dynamic beach-ocean system, posing many problems to coastal communities. However, understanding of the coastal processes is rudimentary.

Relationships between different textural and sedimentological, geochemical, and compositional parameters in varied depositional settings of beach sediments have been used extensively to understand pathways, detrital types, and grain size characteristics to determine sediment provenance or source characteristics (Basu, 1976; Dickinson and Suczek, 1979; Di Giulio *et al.*, 2003; Gawali, Basavaiah, and Hanamgond, 2010; Hanamgond and Chavadi, 1992, 1993; Ibbeken and Schleyer, 1991; Ingersoll, 1990; Kasper-Zubillaga and Dickinson, 2001; Le Pera and Critelli, 1997). However, this is not always so straightforward, because some coastal sands do not necessarily reflect the composition of the source rock (Kasper-Zubillaga and Carranza-Edwards, 2005).

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The purpose of this study is to quantify relationships between season, sediment availability, sediment transport pathways, and beach morphology along the study area.

Study Area

The coastline of Maharashtra is about 720 km long. The littoral lowland there extends from the Arabian Sea to the Western Ghat Escarpment and from north of Mumbai to north of Goa (16° to 19°30′ N) and is well known as Konkan. The coastal ecosystem here is unique and divergent owing to the many geomorphological processes, ranging from tectonic, fluvial, and coastal to aeolian. These processes have acted to variable degrees and over various durations during the quaternary, leaving distinct imprints in the form of dune-ridge complexes, backwaters, lagoons, estuaries, creeks, spits, bar systems, and so on. The coastal stretch of Maharashtra was tectonically active during the Mio–Pliocene period, after which the exogenetic processes became quite powerful (Tandale, 1993). The coastal tract under study is influenced predominantly by semidiurnal tides, and the beaches are microtidal.

The coastal region here is hilly, narrow, and highly dissected with transverse ridges of the Western Ghats, which in many places extend as promontories into the Arabian Sea. The shoreline is very irregular, associated with features like cliffs, notches, promontories, sea caves, intermittent rivers and creeks, estuaries, embayments, submerged shoals, and offshore islands. Oceanography of this region is dominated by the SW monsoon (June–September) and a fair-weather period (October–May). The structural and geological formations of the Vengurla region have been examined in detail by Deendar (1982, 2003), who emphasizes that this area is structurally disturbed, influencing the formation of iron ore, topography, geology, and the drainage patterns. Tandale (1993) asserts the coastal region of Maharashtra was tectonically active during the Miocene–Pliocene periods, which finds support through studies carried out by Rajshekhar and Kumaran (1998). However, Karlekar (2001) laments the lack of a relative chronology of sea-level events along the Konkan coast, some of whose beaches have been studied using remote sensing techniques by Kunte and Wagle (1993, 1994), Hanamgond (2007), and Hanamgond and Mitra (2008).

The area under study (Figure 1) comprises the southernmost region of the Maharashtra coast (Redi to Vengurla), stretching about 20 km (15°44′–15°52′ N, 73°35′–73°40′ E).

METHODS

The upper 3–4-cm surface sediment samples were collected across the beaches at a 10-m interval from a reference point on land (*i.e.*, 0, 10, 20 m, … toward the sea) seasonally premonsoon (May 2003), during monsoon (July 2003), and postmonsoon (November 2003) at 20 selected stations (Figure 1; Vengurla beach stations 1–7, Aravali beach stations 8–14, and Redi beach stations 15–20). Sediment samples were prepared for textural analysis following Ingram (1970) and subjected to textural analysis using ASTM sieves on a Ro-Tap sieve shaker, and grain size parameters were calculated using the Gradistat computer program (Blott and Pye, 2001) for graphic (Folk and Ward, 1957) and moment (Friedman, 1967) methods. The textural studies were undertaken at Govindram Seksaria Science College, Belgaum, Karnataka, India. Geochemical analysis was performed on 33 bulk samples by x-ray florescence (XRF) for determining element concentrations at the environmental magnetism laboratory at Indian Institute of Geomagnetism, Navi Mumbai, India. For sample preparation, 8 gm of dried sediment was ground, of which 4 gm was used for geochemical analysis using Spectro XEPOS XRF spectrometer (AMETEK) by the Turboquant-powders method. For analysis, the standard multichannel analyzer calibration sample from Fluxana was used. Satellite imagery from 2003 premonsoon, monsoon, and postmonsoon and 2004 premonsoon was used to identify sediment movement pathways along the beaches.

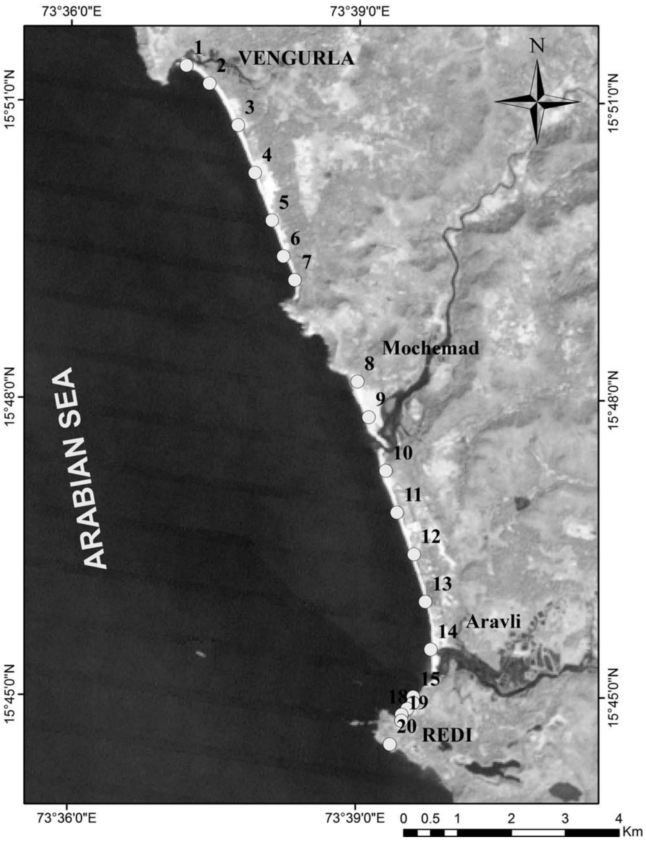

Figure 1. Location map of the study area showing the study sites.

RESULTS

Following are the results of the studies on textural, sediment transport (on- and offshore), geochemical parameters, and their spatial and temporal variations along the study area.

Texture

A large number of studies have explored the role of hydraulic sorting and grain size effects in masking the original source rock composition (Garzanti, Andò, and Vezzoli, 2009; Spagnoli *et al.*, 2008). The textural parameters, such as mean size, inclusive graphic standard deviation, inclusive graphic skewness, and inclusive graphic kurtosis, of Folk and Ward (1957) were calculated for four seasons at 20 locations on the three

Table 1. *Seasonal distribution in percentages of sediment samples from Vengurla to Redi beaches in different grades of grain size parameters.*

	Premonsoon 2003			Monsoon 2003			Postmonsoon 2003		
Inclusive Graphic Grain Size Parameters	Vengurla	Aravali	Redi	Vengurla	Aravali	Redi	Vengurla	Aravali	Redi
Mean size Ø									
CS (0.0–1.0)	—	—	10.71	7.2	—	10.2	—	—	22.0
MS (1.0–2.0)	23.07	5.26	21.42	27.0	7.7	5.0	28.0	12.0	17.4
FS (2.0–3.0)	76.92	94.73	42.85	65.8	92.3	82.0	72.0	88.0	52.0
VFS (3.0–4.0)	—	—	25.0	—	—	2.5	—	—	8.6
Standard Deviation Ø									
VWS (<0.35)	29.23	51.31	3.57	17.0	29.2	7.7	14.0	20.0	8.7
WS (0.35–0.5)	47.7	28.9	60.7	53.6	47.7	25.6	62.5	37.2	34.8
MWS (0.5–0.71)	10.76	14.47	10.71	17.0	17.0	51.3	14.0	32.0	8.7
MS (0.71–1.0)	3.07	3.94	14.3	12.0	6.0	5.0	9.5	9.4	13.0
PS (1.0–2.0)	9.23	—	10.7	—	—	10.2	—	1.4	30.4
VPS (2.0–4.0)	—	—	—	—	—	—	—	—	4.4
Skewness									
VPS (1–0.3)	6.15	3.94	21.42	9.7	6.0	2.5	1.5	—	13.0
PS (0.3–0.1)	15.38	7.81	28.57	31.7	10.7	20.5	4.7	12.0	4.5
NSY (0.1 to −0.1)	16.92	27.63	14.28	41.5	10.7	25.6	28.0	22.7	43.5
NS (−0.1 to −0.3)	30.76	42.10	10.71	17.0	55.4	36.0	56.2	40.0	26.0
VNS (−0.3 to −1.0)	30.76	18.42	25	—	17.0	15.4	9.4	25.3	13.0
Kurtosis									
VPK < 0.67	84.61	89.47	82.14	5.0	38.5	5.0	26.5	—	13.0
PK (0.67–1.11)	10.76	5.26	—	29.0	12.3	20.5	36.0	22.7	21.7
MK (0.9–1.11)	1.53	2.63	3.57	29.0	35.4	28.2	28.0	28.0	21.8
LK (1.11–1.5)	1.53	1.31	3.57	29.0	12.3	36.0	9.5	40.0	26.0
VLK (1.5–3.0)	—	—	3.57	7.0	—	10.3	—	9.3	17.5
ELK (>3.0)	1.53	1.31	7.14	—	—	—	—	—	—

Mean size: CS = coarse sand, MS = medium sand, FS = fine sand, VFS = very fine sand; sorting: VWS = very well sorted, WS = well sorted, MWS = moderately well sorted, MS = moderately sorted, PS = poorly sorted, VPS = very poorly sorted; skewness: VNS = very negatively skewed, NS = negatively skewed, NSY = nearly symmetrically skewed, PSK = positively skewed, VPS = very positively skewed; kurtosis: VPK = very platykurtic, PK= platykurtic, MK = mesokurtic, LK = leptokurtic, VLK = very leptokurtic, ELK = extremely leptokurtic.

beaches. Table 1 shows the percentages of samples present in different grades of texture. The classifications are made according to Wentworth (1922) for mean size and Folk and Ward (1957) for the rest.

The moment textural parameters were used to delineate the sediment movement using the McLaren and Bowles (1985) model. The mean is taken to reflect the general average of the size of sediments under study. This parameter is influenced by source and the depositional setting, as well as the erosive agents. Standard deviation gives a sense of how the sorting or the degree of uniformity is present in particle size distribution. Skewness measures asymmetry of particle size distribution. According to Folk and Ward (1957), graphic kurtosis is a qualitative measure of sediments already sorted out elsewhere in a high-energy environment that are later transported to some other environment where they are deposited.

The interrelationship between different grain size parameters and the characteristics of depositional agent are deciphered through bivariate plots (Figures 2 and 3).

Vengurla Beach

The grain size parameters (Table 1) reveal how mean size varies between medium and fine sand premonsoon and postmonsoon (23% and 77%; and 28% and 72%, respectively) and between coarse to medium to fine sand during monsoon (7%, 27%, and 66%, respectively). The standard deviation varies premonsoon from very well sorted (VWS; 29%), well sorted (WS; 48%), moderately well sorted (MWS; 11%), moderately sorted (MS; 3%), to poorly sorted (PS; 9%); during monsoon, VWS is 17%, WS 54%, MWS 17%, and MS 12%; and postmonsoon the standard deviation changes to 14% VWS, 63% WS, 14% MWS, and 9% MS during the study period. The skewness of the sediments collected premonsoon range from 6% very positively skewed, 15% positively skewed, 17% nearly symmetrically skewed, 31% negatively skewed, and 31% very negatively skewed. During monsoon, very positively skewed sediments make up 10%, positively skewed 32%, nearly symmetrically skewed 42%, and negatively skewed 17%. The kurtosis of the sediments varies from very platykurtic (VPK; 85%), to platykurtic (PK; 11%), to mesokurtic (MK), to leptokurtic (LK; 2% each), to extremely leptokurtic (ELK; 2%) premonsoon. A drastic change is seen during monsoon in kurtosis, which is 5% VPK; 29% PK, MK, and LK each; and 7% very leptokurtic (VLK). Postmonsoon, the situation changes again, wherein VPK is 27%, PK is 36%, MK is 28%, and LK is 10%.

Aravali Beach

Mean grain size (Table 1) varies from medium sand (premonsoon 5%, monsoon 8%, and postmonsoon 12%) to fine sand (premonsoon 95%, during monsoon 92%, and postmonsoon 88%). A slight decreasing trend is observed in fine sand from premonsoon to postmonsoon. The standard deviation for sorting varies from VWS (51%), to WS (29%), to MWS (14%), to MS (4%). Most are well-sorted premonsoon and during the monsoon and postmonsoon seasons. The skewness of the sediments varies from very positively skewed (4%), positively skewed (8%), near symmetrically skewed (28%), negatively skewed (42%), to very negatively skewed (18%) premonsoon. The bulk of the sediment is negatively skewed. The kurtosis of

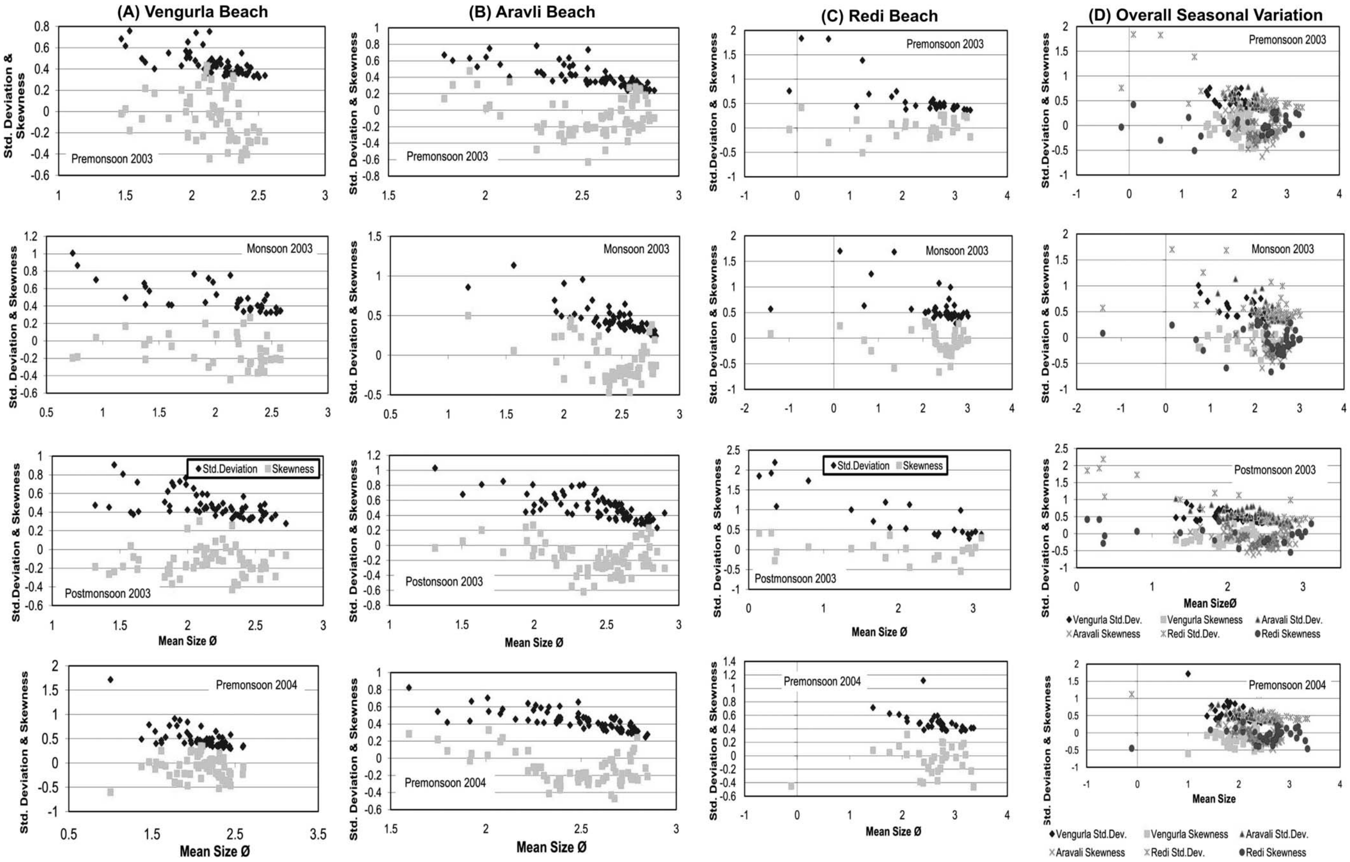

Figure 2. Bivariate plots showing relationship of mean size vs. standard deviation and skewness separately for Vengurla, Aravali, and Redi beaches, as well as the overall seasonal variation for better discrimination of locations and seasons.

the sediments ranges from 89% VPK, 5% PK, 3% MK, 1% LK, to 1% ELK premonsoon. During monsoon sand is 89% VPK, 5% PK, 3% MK, and 1% each LK and ELK. The bulk of sand grains are very platykurtic premonsoon and during monsoon season, but leptokurtic postmonsoon.

Redi Beach

The mean size of sand oscillates between coarse (11%), medium (21%), fine (43%), and very fine sand (25%) premonsoon. During monsoon coarse sand is 10%, medium sand 5%, fine sand 82%, and very fine sand 3%. Postmonsoon coarse sand is 22%, medium sand 17%, fine sand 52%, and very fine sand 9%. The percentage of coarse sand is higher postmonsoon. Fine sand, on the other hand, is greater premonsoon and during monsoon. The standard deviation depicts sand sorting to be VWS 4%, WS 61%, MWS 11%, MS 14%, and PS 11% premonsoon. During monsoon VWS is 8%, WS 26%, MWS 51%, MS 5%, and PS 10%. Postmonsoon VWS is 9%, WS 35%, MWS 9%, MS 13%, PS 30%, and VPS 4%. The skewness of the sediments shows significant variation and mixing, and it varies from very positively to very negatively skewed: 21% very positively skewed, 29% positively skewed, 14% nearly symmetrically skewed, 11% negatively skewed, and 25% very negatively skewed premonsoon. During monsoon skewness is 3% very positively skewed, 21% positively skewed, 26% nearly symmetrically skewed, 36% negatively skewed, and 15% very negatively skewed. Postmonsoon 13% is very positively skewed, 5% positively skewed, 44% nearly symmetrically skewed, 26% negatively skewed, and 13% very negatively skewed. The kurtosis of sediments varies from very platykurtic premonsoon to leptokurtic during the remaining two seasons.

Bivariate Plots

The relationship between mean size and standard deviation with skewness for all the seasons is presented in Figure 2A–C, which reveals that as the degree of sorting increases (standard deviation decreases) the mean size also increases. This signifies that the finer the sand, the better the sorting (Griffiths, 1967; Inman, 1949). The figures that plot mean size and skewness reveal a sinusoidal (V) trend. In general, skewness values are seen to move from positive toward negative within the mean size range from about 1.5 to 2.3Ø. Around 2.4 to 2.5Ø the trend reverses and continues up to 2.8Ø.

Figure 2D also shows the overall seasonal textural variation between the three beaches, revealing that the sediments of Vengurla, Aravali, and Redi have clustered into separate entities. The Redi beach sediments are coarser, ill sorted, highly skewed, and highly kurtotic compared with the rest of

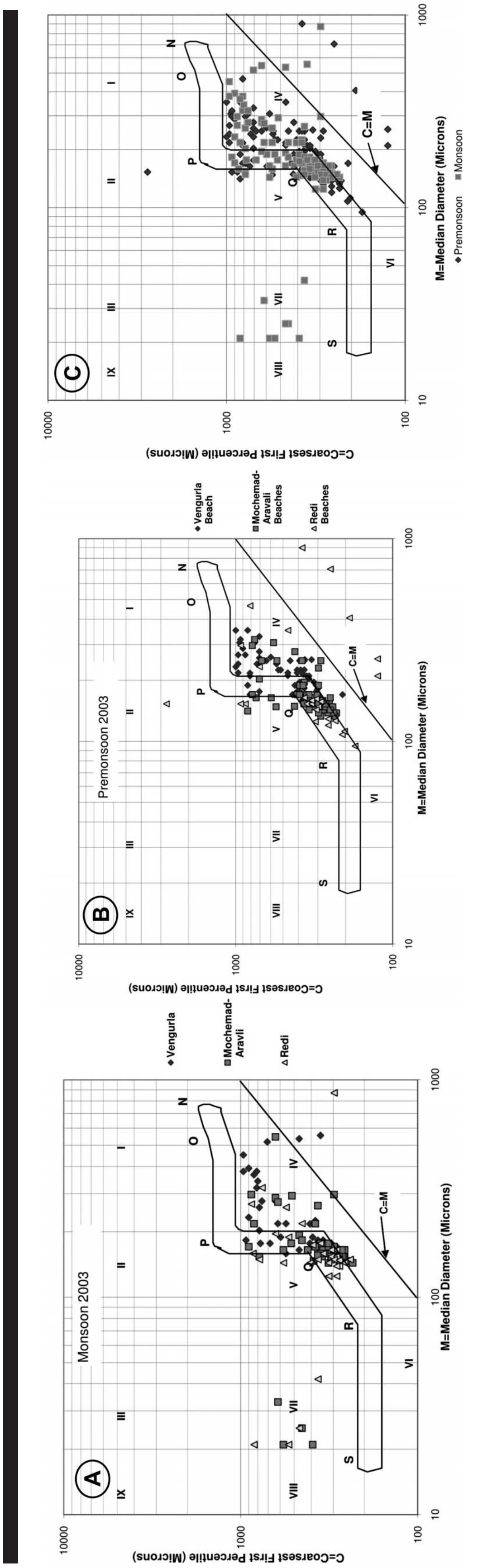

Figure 3. CM patterns for the sediments of the study area, which discriminate individual beaches in a particular season (A, B) with an overall seasonal variation (C) for the entire stretch.

the beaches. Between Vengurla and Aravali beaches, the Vengurla beach sediments are coarser than those of Aravali.

CM Pattern

Passega (1964) introduced C-M plots to evaluate hydrodynamic forces working during the deposition of sediments. The CM patterns (Figure 3) represent the OPQRS field of Passega (1964). The sediments fall within the zone of "beach deposits" defined by Passega (1964) and suggest the traction currents are the transport mechanism. Most of the sands are transported as graded suspension and rolling. The sediments of the study area fall predominantly in regions IV and V (Passega and Byramjee, 1969).

It can be seen from the plots that the monsoon season samples fall in the N–S region, indicating the inputs of rolled, traction, and suspension sediments. The summer season is characterized by samples falling in the N–R region, which indicates the inputs of rolling and traction sediments. However, the suspension and rolling mode of sedimentation are less significant compared with the tractive mode of sediments.

The sediments occupying positions IV and V premonsoon at Vengurla beach are as follows: IV = 61.5%, V = 38.5%; Aravali beach: IV = 14.5%, V = 86.5%; Redi beach: IV = 35.7%, V = 18.6%, and during monsoon, Vengurla beach: IV = 15.2%, V = 13%; Aravali beach: IV = 7.6%, V = 33%; Redi beach: IV = 5.8%, V = 18.6%.

The sediments falling in regions IV and V are suspension sediments that may contain rolled grains smaller than 1 mm. Types IV and V are generally graded suspension sediments: type IV are high and type V are moderate turbulence deposits. Thus, it can be deduced that the sediments of the study area are deposited under moderate to high energy conditions. At Redi, the sediments are scattered between coarse to fine, indicating turbulence owing to mixing activity (between stations 14 and 19) by River Redi and River Terekhol (around station 20).

Apart from these examples, the moment textural parameters were used to delineate the sediment movement using the McLaren and Bowles (1985) model. Sediment transport paths, using the summary of the number of pairs of sediment samples producing the paths, are presented in Figures 4 and 5.

On- and Offshore Sediment Movement

The direction of sediment movement was tracked for four seasons following McLaren and Bowles (1985). The majority of the trends were significantly offshore during premonsoon 2003 and onshore during premonsoon 2004 at Vengurla beach. However, at Aravali beach, the trend was offshore during premonsoon 2003 and strongly onshore with a weak offshore trend during premonsoon 2004. The sediments at stations 1, 2, 6, 8, 11, and 13 (with a 1% level of significance) show a low-energy regime (case B: fine, better sorted, and negatively skewed) of offshore sediment movement. The sediments at stations 14 (with a 1% level of significance) show a low-energy regime (case B) of onshore sediment movement. This clearly indicates and supports the overall loss of beach at Vengurla and gain at Aravali during premonsoon 2004.

During monsoon 2003, the sediments of Vengurla beach at stations 1 and 2 (with a 1% level of significance) show a low-energy regime of offshore sediment movement. Whereas, at

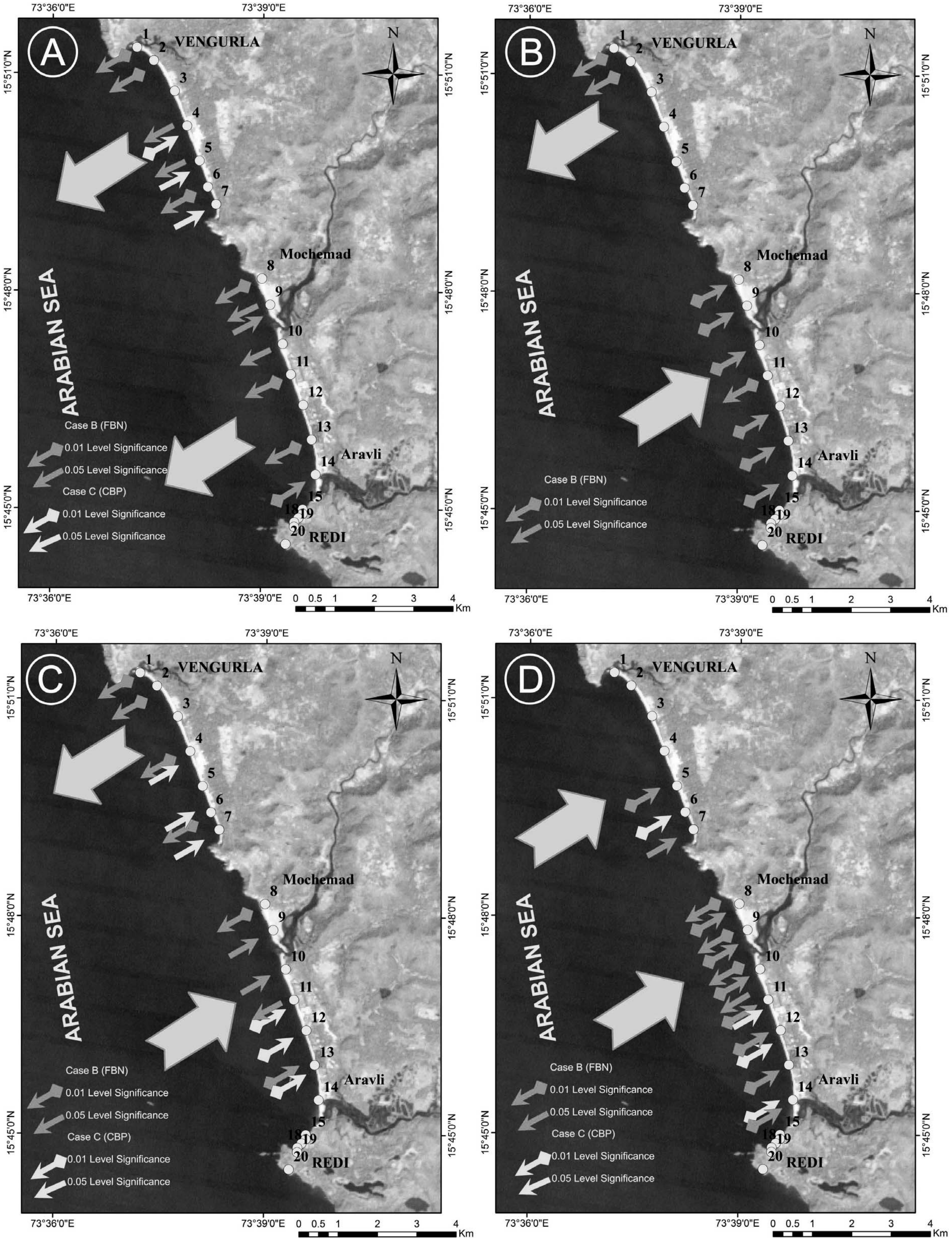

Figure 4. Sediment transport paths deduced across the study area during (A) premonsoon 2003, (B) monsoon 2003, (C) postmonsoon 2003, and (D) premonsoon 2004, showing an on- and offshore exchange of sediments.

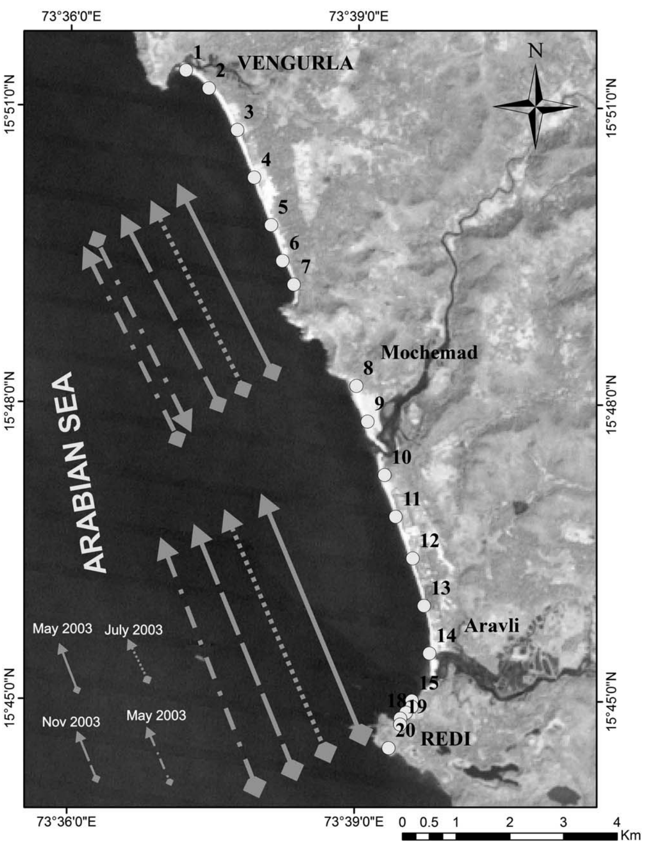

Figure 5. Seasonal alongshore sediment transport paths deduced for the study area using grain size trends.

Aravali all stations, except station 11, show a low-energy regime (with a 5% level of significance) of onshore sediment movement. This fact clearly indicates that the sediment from Vengurla beach bypasses or is under circulation (finer sediments) to Aravali beach.

During postmonsoon 2003, the sediments of Vengurla beach at stations 1, 3, 4, and 6 (with a 1% level of significance) show a low-energy regime of offshore sediment movement, whereas stations 4, 6, and 7 (with a 5% level of significance) show a high-energy regime (case C: coarse, better sorted, and positively skewed) of onshore sediment movement. The sediments of Aravali beach at stations 9 and 10 (with a 5% level of significance) and station 13 (with a 1% level of significance) show a low-energy regime of onshore sediment movement, whereas stations 11 and 12 (with a 1% level of significance) show a high-energy regime of onshore sediment movement.

Longshore Sediment Movement

In general, the sediments of Aravali and Vengurla beaches during the study show a northerly sediment movement trend (Figure 5). However, during premonsoon 2004, the sediments at Vengurla beach show both southerly and northerly sediment movement with the low-energy regime (case B).

The observed northerly sediment movement trend is mainly due to sediment input from Rivers Redi and Terekhol situated at the southern end of the study area.

Linear Discrimination

The multivariate linear discriminant function analysis (Sahu, 1964) was used for the sediments of the study area for all seasons. As observed in Table 2, the majority of the sediment samples (71–81%) of the study area during all seasons falls in the beach environment and 18–28% of the sediment samples represent aeolian processes (Y1). The aeolian processes are stronger during postmonsoon season. Further discrimination among beach and shallow marine processes (Y2), shows that the sediments of the study area predominantly represent a shallow marine environment (66–74%), whereas 26–34% represent beach processes. The discrimination between marine and fluvial processes (Y3) shows that the majority of sediments represent marine processes (94–98%) with some fluvial interference (1.8–5.6%). The fluvial interference was observed during monsoon and postmonsoon season. It can be inferred that the sediments in the present-day beaches must have been deposited in a shallow marine environment, and in due course of time, marine regression must have led to the development of the present-day shorelines (Angusamy and Rajamanickam, 2007).

Geochemical Parameters

The differences in the proportions of quartz, feldspar, amphiboles, pyroxenes, olivine, and heavy minerals in source rocks can define the geochemical composition of beach sands. Occasionally, mean grain size might not be relevant when interpreting the differences in geochemical compositions of beach sands, where the beaches are largely controlled by sediments derived from basic volcanic rocks composed mostly of dense minerals (Marsaglia, 1993). Geochemical analysis was carried on 33 samples from the three beaches collected during three seasons. The results are shown in Figure 6, and the distribution of elements is discussed separately here.

Table 2. *Percent abundance of sediment samples obtained by linear discriminant function analysis for the study area during different seasons for various depositional environments.*

		% Abundance					
		Aeolian:Beach (Y1)		Beach:Shallow Marine (Y2)		Shallow Marine:Fluvial (Y3)	
Seasons	Total Samples	Aeolian (<−2.7411)	Beach (>−2.7411)	Beach (<65.3650)	Shallow Marine (>65.3650)	Marine (<−7.4190)	Shallow Fluvial (>−7.4190)
Premonsoon 2003	169	19	81	33.7	66.3	98.2	1.8
Monsoon 2003	145	22	78	29.6	70.4	95.2	4.8
Postmonsoon 2003	162	28.4	71.6	26	74	94.4	5.6

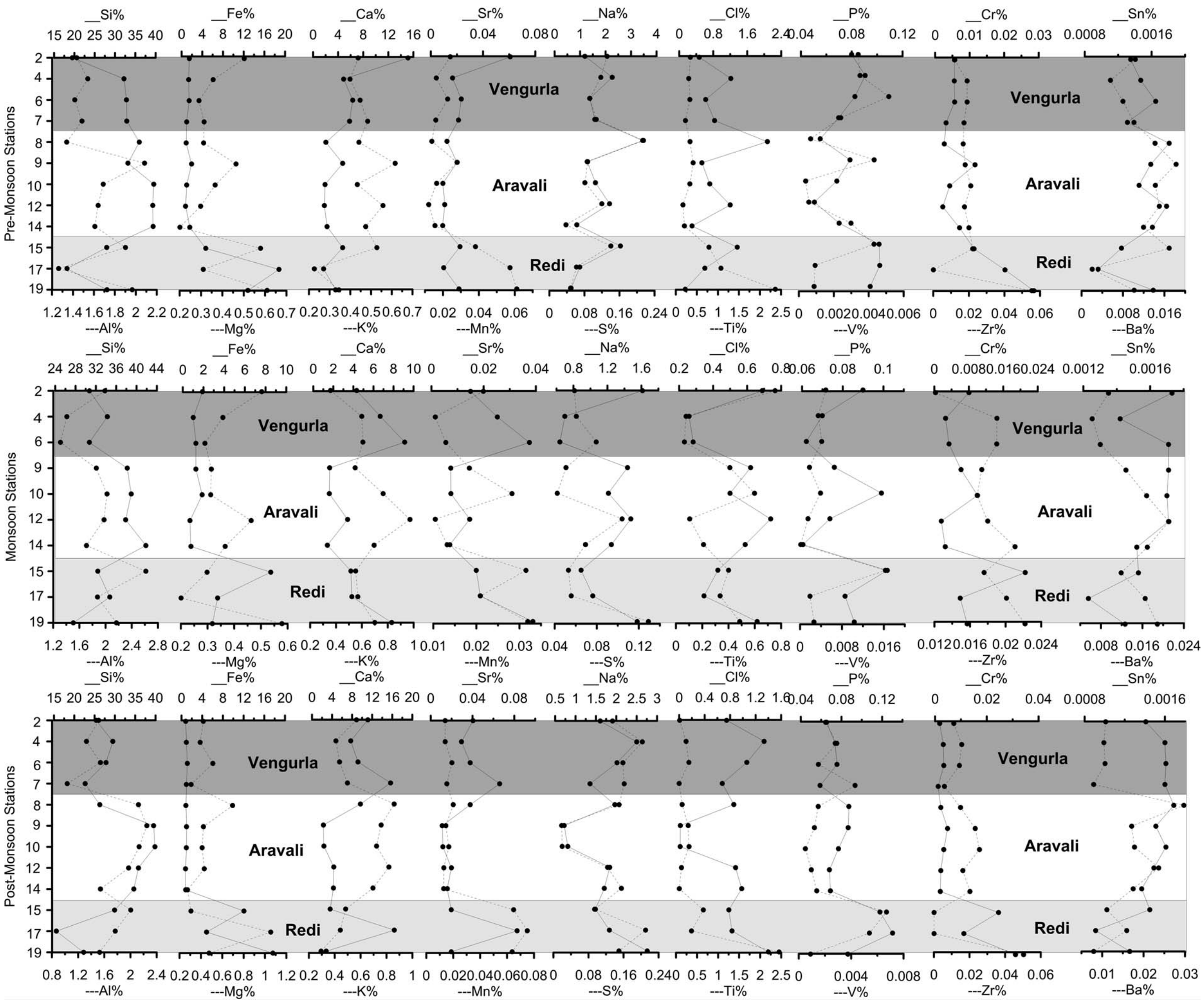

Figure 6. Distribution of elements showing the geochemical variability of the study area.

Vengurla Beach

Si (Figure 6) premonsoon increases from station 2 and is almost constant at stations 4, 6, and 7; during monsoon, Si increases at stations 2 and 4 and decreases at station 6. The concentration of Si is found to be on the wane postmonsoon compared with premonsoon and monsoon seasons. Concentration of Al at Vengurla rises and falls at alternate stations (Figure 6) premonsoon. An overall increase in concentration during monsoon season and a drop in quantity postmonsoon to the level of premonsoon is clearly seen. Fe is almost uniform at the examined stations premonsoon, the quantity of which is almost the same during monsoon and considerably decreased postmonsoon. The concentration of Mg decreases drastically from station 2 to 4 and gradually decreases further to station 7 premonsoon. The quantity of Mg decreases by almost half at station 2 during monsoon compared with premonsoon and continues to fall at stations 4 and 6, as well. The postmonsoon trend is increasing, which drops at station 7. Ca decreases from station 2 to 4, slightly increases at station 6, and marginally falls at station 7 premonsoon. During monsoon, the concentration is much less at station 2 compared with premonsoon, but it is on the rise at stations 4 and 6. This trend continues postmonsoon, as well, where the concentration is increased during the monsoon season. K increases from station 2 to 7, except for a small drop at station 4 premonsoon, and increases during monsoon and postmonsoon at all the locations. Sr at station 2 is greater premonsoon, falls drastically during monsoon season, and marginally increases postmonsoon. Sr decreases premonsoon, doubles during monsoon, and slightly increases postmonsoon at stations 4 and 6. The element marginally falls at station 7 premonsoon and increases postmonsoon. Mn follows the trend of Sr premonsoon but is opposite during monsoon and postmonsoon. Its concentration increases during monsoon and postmonsoon. Na increases from station 2 to station 4, falls at station 6, and marginally rises at station 7 premonsoon. At the same sampling locations it rises then falls drastically and continues to fall during monsoon. The trend seems to be increasing at the sampled locations postmonsoon. S displays a similar trend as Na premonsoon, but almost the opposite trend in the remaining two seasons. The spread of Cl is almost uniform premonsoon, fluctuating during monsoon and postmonsoon, with an increase in quantity seen more postmonsoon than monsoon and premonsoon. Ti increases at station 4 from the initial values at station 2 premonsoon then decreases (station 6) and marginally increases at station 7. It behaves similar to the concentration of Cl during monsoon, although its concentration drops during monsoon. The quantity further decreases postmonsoon.

Concentration of P decreases from station 2 to 7 premonsoon, with the same trend continuing during monsoon and postmonsoon. The overall quantity of this element is greater during monsoon and postmonsoon. The percentage of V is greater at station 6 premonsoon, but during monsoon and postmonsoon it seems to decrease considerably. The concentration of Cr is almost uniform at Vengurla beach, with a slight decrease toward station 7 premonsoon. It decreases considerably during monsoon, station 4 having the lowest values, which are further seen to decrease postmonsoon. Zr is lowest at station 2 and increases at stations 4 and 6, marginally decreasing at station 7 premonsoon. The concentration seems to have increased at station 2 during monsoon but decreased at the other stations, which seems to be the case for postmonsoon as well. Tin gradually increases from station 2 to 6 and decreases at station 7 premonsoon. The concentration decreases at all stations during monsoon, which marginally increase postmonsoon.

At Vengurla, Cl is highly correlated with Na and Mg premonsoon, and with Na, P, and K postmonsoon. The monsoon samples, however, show an increase in concentrations of elements. A very high correlation of Cl is seen with elements like P, Ti, Cr, Mn, Fe, and Zr, but correlates negatively with K. During the premonsoon period, Cl, Na, Mg, Ti, Zr, Si, Ca, Sr, Sn, P, and K are strongly associated.

Aravali Beach

Percentage of Si is greater in all seasons at this beach compared with Vengurla and Redi beaches (Figure 6). Its percentage increases from station 8 to 14, with a small dip at station 9 premonsoon. The percentage of Si increases during monsoon at all stations and decreases postmonsoon. Si decreases consistently from station 8 to 14, except at station 9, where a sharp increase is seen. The concentration of Al is greater in all seasons relative to Vengurla and Redi. Al from station 8 increases at station 9, where it gradually decreases to station 14 premonsoon. During monsoon, the percentage of Al increases, from gradually increasing at stations 9 and 10 to gradually decreasing at stations 12 and 14. The percentage of Al marginally decreases postmonsoon, and a decreasing trend is seen from stations 8 to 14. Fe is evenly spread without showing much variation in all the three seasons, although it marginally seems to have increased during monsoon and fallen postmonsoon. Mg exhibits a decreasing trend, except for a small hump at station 9 premonsoon. The concentration decreases during monsoon, with a slight increase at station 12. The overall concentration increases postmonsoon, with a high at station 8, a low at station 14, and the intervening stations showing uniform concentration. Ca is uniformly spread across the beach during all seasons, with slightly enhanced values at stations 9, 12, and 14. The percentage of Ca is greater postmonsoon compared with the other two seasons. K fluctuates in concentration from station to station in all seasons. Its concentration is greater in monsoon than pre- or postmonsoon. Sr percentage is almost uniform at all stations in all seasons, although the overall concentration is greater postmonsoon and premonsoon than monsoon. The same is true for Mn. Na exhibits large fluctuations in concentration during all seasons, and its concentration is greater premonsoon than during monsoon and postmonsoon. S shows the same pattern of variation as Na, except for an opposing trend at stations 9 and 10 during monsoon and at station 19 postmonsoon. Cl fluctuates at all stations during all three seasons. Its concentration is highest premonsoon at station 8 and lowest at stations 9 and 10 postmonsoon. Ti has low-amplitude fluctuations pre- and postmonsoon and is relatively enhanced during monsoon. The percentage is more during monsoon than pre- and postmonsoon.

Percentage of P fluctuates from station to station premonsoon and during monsoon and is almost uniform, though slightly decreasing, postmonsoon. The concentration is slightly greater postmonsoon than the other two seasons. V variations are almost similar to those of P during all seasons. Cr variations are uniform postmonsoon, mildly fluctuating premonsoon, and more fluctuating during monsoon, when its concentration is slightly greater. Zr gradually increases premonsoon, postmonsoon, and during monsoon. The overall percentage of this element is greater during monsoon followed by postmonsoon and premonsoon. Sn is slightly greater at this beach premonsoon and during monsoon, which decreases postmonsoon compared with the other two beaches. Low-amplitude variations are seen pre- and postmonsoon, with almost uniform variation for three stations that then decreases at stations 12 and 14 during monsoon. Ba shows mild fluctuations at all stations in all seasons. Its percentage is comparatively greater postmonsoon.

A strong association is seen between Na, Cl, S, Ca, Cr, Mn, Sr, Fe, V, P, Si, and Zr premonsoon. Cl, S, Ca, Cr, Mn, Sr, Fe, V, P, Si, Ti, and Ba are strongly associated during monsoon. The postmonsoon samples exhibit strong association among Na, Cl, S, Ti, Cr, Fe, Zr, Si, Ba, K, Ca, Sr, Mn, and Sn.

Redi Beach

Compared with the other two beaches, the percentage of Si is low at this beach, and it is lowest at station 17 pre- and postmonsoon. The Si value is enhanced during monsoon. Like Si, the concentration of Al is also low. The percentage increases during monsoon (Figure 6). Unlike Si and Al, Fe is increasing at all sampling locations analyzed for geochemical elements for all seasons. Fe seems to rise and fall with change in station. Percentage of Mg also displays changes and seems to rise postmonsoon. Compared with the other two beaches, Ca is less premonsoon and increased during monsoon and postmonsoon. K decreases considerably at station 17 from station 15 premonsoon and marginally increases at station 19. It increases during monsoon and continues this trend from station 15 to 19. Postmonsoon, K decreases continuously to station 19. Sr at station 17 shows a decrease from its adjoining stations premonsoon and a slight increase during monsoon. Sr at station 17 shows a big increase compared with stations 15 and 19 postmonsoon. Mn is comparatively greater than at the other two beaches premonsoon. The percentage comes down marginally during monsoon and picks up again postmonsoon. The falling trend of Na at Aravali continues at Redi premonsoon, which reverses during monsoon and continues postmonsoon. The percentage of Na is marginally greater postmonsoon. Percentage of S displays the same kind of variation as for Na, except at station 17 postmonsoon. S is greater postmonsoon compared with the other two seasons. Cl continuously decreases at all stations in all seasons and is comparatively greater postmonsoon. Ti increases premonsoon, decreases during monsoon, and again increases postmonsoon. The percentage of this element is greater premonsoon than in the other two seasons.

Percentage of P is less premonsoon, increases during monsoon and postmonsoon, being greater postmonsoon. The same holds true for V. Cr percentage is greater at this beach than at the other two beaches in all seasons. It is greater pre- and postmonsoon than during monsoon. Zr varies mildly at all stations in all seasons. Its percentage is marginally greater postmonsoon (Figure 4). Sn is lower at this beach than the two other and is greater postmonsoon. Ba increases during monsoon.

DISCUSSION

Physical and chemical weathering processes break down and disintegrate the bedrock into smaller fragments under the influence of water, wind, and other climatic processes that operate in tropical climate regions such as the west coast of India. The beaches along the Konkan region are recipients of sediment from a number of sources. The material that makes up the beaches is a reflection of the source, which needs to be identified to better understand the physicochemical processes operating in its near and far regions.

The three beaches studied are exposed to different environmental conditions, wherein the detrital pattern of accumulation, erosion, or both is quite distinct from each other. They also share a different geochemical realm that is sometimes at variance with one another. The variation at Vengurla can be inferred to be season dependent, wherein the hinterland seems to be drained vigorously by the monsoonal precipitation, as revealed by the strong association of Ba in the monsoon samples with Mg, Ca, and Sr. Ba is relatively less mobile compared with Mg, Ca, and Sr (Das and Krishnaswamy, 2006). The geochemical characteristics of Aravali are different from those of Vengurla.

Redi beach is characterized by a strong association of all elements with one another, irrespective of the season or conditions. This very significant feature sets it apart from the other two beaches studied. It must be noted that this beach has copious iron ore deposits (banded hematite, quartzite, and hematite), with mining dumps stacked right above it. Additionally, the ore is added to the beach by spilling during transportation via jetty (River Redi and sea confluence). Iron ore in the Redi and surrounding areas is associated with banded ferruginous quartzites and Precambrian ferruginous phyllites. The iron ore consists essentially of hematite and partly of magnetite, limonite, and goethite, which occur as reefs and lensoidal bodies. Because the Redi headland is separated by River Redi in the north and River Terekhol in the south, this configuration might not allow the minerals to be redistributed along its northern and southern sectors.

The presence of different element groups is related to the mineralogical constituents, detrital pathways, and physicochemical processes, which in turn are influenced by climate, abrasion, and sorting during sediment transportation and the end geomorphology. The chief source of Si to these beaches is quartz, and feldspars provide K. Elements Sc, Ti, V, and Mn might come mostly from the pyroxenes and amphiboles. Ti and Fe were likely released from the banded hematite formations. Gujar, Ambre, and Mislankar (2007) studied heavy mineral placers from Vijaydurg to Redi and found the opaque minerals to contain ilmenite in areas of significant concentration and areas of localized concentration (43.07% and 11.02%, respectively), magnetite (58.15% and 8.72%), and chromite (up to 10.09%). The presence of nutrient elements on these beaches (*e.g.*, Sr, Cd, Ba, K, V, and Cr) can nourish beach microorganisms, leading to healthy environmental conditions. The metamorphic rocks of the hinterland contribute substantially to the sands of the beaches, apart from the Deccan traps. Thus, the geology of the area plays a big role in accumulation of sands at these three beaches, which are reworked by the wind and current regime prevalent in this coastal tract.

The study also suggests, especially at Vengurla and Aravali, a coarsening trend seaward in low water level and breaker samples. This occurs because the point just seaward of the low water level or backwash or breaker level is the place of maximum turbulence and the high–wave energy zone (Bascom, 1951; King, 1972). Hydrodynamic processes (Kurian *et al.*, 2000) and alongshore and cross-shore movement of sediments (Chandrasekar *et al.*, 2003) are also important sources of placer formation along the beaches. In contrast, Li *et al.* (2002) find sediment transport processes in the swash zone to be of fundamental importance to beach morphology and shoreline stability. Additionally, the heavy mineral concentration is not just linked to the source but is also controlled by shoreline configuration and seasonal wave climate (Chandrasekar *et al.*, 2005). The source of sediments and the strength and energy of the current carrying the sediments influence grain size characters and mineralogical composition (Chavadi and Hegde, 1989). In the direction of transport, the grain size of sediment decreases progressively (Pettijohn, 1975): the sediment becomes finer, better sorted, and very positively skewed (McLaren and Bowles, 1985), whereas light minerals such as feldspars are impoverished along the direction of transport (Plumley 1948; Russel and Tylor, 1937). Groundwater percolation produces rill structures (Hanamgond, 1990), which remove finer particles and leave behind the coarser, sometimes rolling coarser, or both types of grains or pebbles when inflow is stronger. Hegde, Shalini, and Kanchanagouri (2006) have found the concentration of heavy minerals to be associated with the erosional profile, indicating their concentration is influenced more by the strong winnowing action of waves and less by the selective transport through alongshore currents.

The heavy mineral placers along the Konkan coast are enriched in ilmenite and magnetite, along with the heavy granitic and metamorphic index minerals like zircon, tourmaline, kyanite, and staurolite, although their concentration pattern varies from bay to bay (Gujar, Rajamanickam, and Wagle, 2000; Siddiquie and Rajamanickam, 1979; Siddiquie *et al.*, 1982; Wagle, Gujar, and Mislankar, 1989). In the present study, black sand layers in the beach scarp and on the surface (especially at Redi beach) have been noted. At the northern end of Aravali beach and the Mochemad headland, pink garnet deposits have been observed. Some of the Mochemad headland rocks also exhibit the presence of coarse-grained garnet minerals in the schist rocks (Hanamgond 2007).

The morphological studies carried out by Hanamgond (2007) along these beaches in general revealed an accreting (prograding) trend postmonsoon and erosional (retrograding) trend premonsoon and during the monsoon season, indicating episodic as well as cyclic morphological processes. Accumulation or removal of sediment on- or offshore is ascribed to the action of waves, tides, and longshore currents. The beaches here follow the general growing tendency premonsoon and postmonsoon, wherein the beaches exhibit maximum growth. The erosional tendency, however, was observed during June and July 2003, which is in line with general observations along the west coast of India. Thus, the differences in magnitude of placer sands and magnetic mineral accumulation on this coastal stretch are primarily due to concentration of sand as a function of shoreline geometry and a changing seasonal wave climate. Apart from the cyclic changes in the wave and wind patterns, the morphological behavior can be attributed to the physical setting of these beaches.

The longshore currents observed along these beaches (Hanamgond, 2007) revealed that northerly currents prevail during fair-weather seasons and southerly currents occur mainly during monsoon season. However, at Redi beach, this trend does not exist, perhaps because of the orientation and shelter of the beach.

Beach sands tend to be sorted according to the energy levels to which it is exposed. It thus signifies that beaches exposed to higher levels of wave energy are expected to be composed wholly of coarser sediments. Fine-grained and better sorted mature sands composing quartz-rich entities, on the other hand, may be inherited from selective processes, such as longshore transport and wind patterns. The cross-shore variations in grain size parameters, especially mean size and sorting, show a fining trend seaward along Vengurla beach and a coarsening trend seaward along Aravali and Redi beaches. The fining trend seaward at Vengurla beach indicates normal sediment dispersion and foreshore sediments that are under the influence of swash-backwash phenomena, giving rise to good sorting and negative skewness. The coarsening trend seaward along Redi and Aravali indicates the influence of higher energy conditions, mainly because of the influence of mixing River Redi currents and oceanic waves, producing a higher energy regime, especially at southern Aravali and Redi beaches. The sorting decreases seaward in all the beaches, except at Aravali, which displays both mixed improving and worsening trends.

The Redi beach sediments are coarser, ill sorted, highly skewed, and highly kurtotic compared with the other two beaches. In general, Vengurla beach sediments are coarser than Aravali, indicating that the sediments of the study area are deposited under moderate to high-energy conditions. Sediments of the Redi beach remain scattered between coarse to fine, indicating turbulence from the mixing of Rivers Redi and Terekhol with the ocean. The high correlation between different elements can be attributed to the distinct morphology of this beach coupled with anthropogenic influences. The sediments coming toward these beaches are carried by traction currents of moderate to high-energy conditions. It also reveals that the majority of sediments are transported as graded suspension, indicating sediments are of relict type. The rounded to well-rounded gravels and pebbles found along Redi beach throughout the year supports sediment reworking. The role of longshore currents in the mixing and homogenization of sands in these three beaches located next to each other is not significant.

CONCLUSIONS

Accumulation/erosion and dispersal of elements is dependent on season, wherein enrichment of some elements is greater postmonsoon. Apart from Si, which is found in copious amounts, the other major elements exhibit curious seasonal erosion and accumulation. Along the Vengurla beach, with respect to premonsoon concentrations, Na decreases about 10% and increases almost 6% during monsoon and postmonsoon, respectively. Mg decreases 4% during monsoon and increases 6% postmonsoon. Al increases 4% during monsoon and decreases 3% postmonsoon. Ca decreases 8% during monsoon and increases 14% postmonsoon. Ti decreases 4% and 15% during monsoon and postmonsoon, respectively. Fe increases 1% during monsoon and decreases 10% postmonsoon. Along the Aravali beach, with respect to the premonsoon concentration, Na decreases about 12% and 9% during monsoon and postmonsoon, respectively. Mg decreases 0.3% during monsoon and increases 11% postmonsoon. Al increases 7% and 6% during monsoon and postmonsoon, respectively. Ca increases 2% and 18% in monsoon and postmonsoon, respectively. Ti increases 13% in monsoon but decreases 13% postmonsoon. Fe decreases 12% and 8% during monsoon and postmonsoon, respectively.

Percentage of V, Cr, and Zr are greater premonsoon; Si, Al, K, Sr, Mn, Ti, and P during monsoon; and Mg, Ca, K, Mn, Na, S, Cl, and P postmonsoon at Vengurla beach. At Aravali beach, the percentage of Si and Al is greater than that observed at Vengurla or Redi. The percentage of Mn, Na, S, and Cl is greater premonsoon; Si, Al, Fe, K, Ti, Cr, and Zr are greater during monsoon compared with the other two seasons; and Mg, Ca, Sr, Mn, P, and V are greater postmonsoon. At Redi, Cr and Ca are greater than at the two other beaches. Percentage of Fe is greater in all seasons at Redi. Mn and Ti are quantitatively greater premonsoon; Si, Al, Fe, and K are greater during monsoon; Fe, Mg, Ca, Sr, Na, S, Cl, P, V, Cr, and Zr are greater postmonsoon.

These seasonal changes are attributable to changing wind and wave climate, acting differently at these beaches even though situated close to each other. Transport paths in the wave-dominated environment of Sindhudurg is deciphered using grain size parameters to understand the direction of sediment transport and to define areas of erosion, accretion, and equilibrium. These beaches exhibit an accreting trend postmonsoon. Erosion is the dominant process occurring premonsoon and during monsoon, which reveals that ongoing episodic and cyclic morphological processes are operative in this coastal belt.

The intensity of longshore currents is greater at Vengurla and Aravali, but diminished along Redi beach. Northerly currents were seen to prevail during a fair-weather period and southerly currents occur mainly during monsoon season. Seaward grain size fining occurs along Vengurla beach (swash-backwash phenomenon) and a coarsening trend seaward along Aravali and Redi beaches (high-energy conditions). Thus, the sediments of the study area are deposited under moderate to high-energy conditions. The prominent transport mechanism for sediment dispersal is traction currents.

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