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Mineral Magnetic Properties of Sediments of Beaches, Redi–Vengurla Coast, Central West Coast of India: A Seasonal Characterization and Provenance Study

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ABSTRACT

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The beaches under study are characterized by distinctly different magnetic signatures in terms of their concentration and magnetic grain sizes. Seasonal variation in accumulation and erosion is seen at Vengurla Beach (Stations 1–7), which is moderate to very low premonsoon, high to low during monsoon season, and low to very low postmonsoon. Presence of fine single domain magnetic grains is moderate to high premonsoon, moderate to low during monsoon, and low postmonsoon at stations 1, 4, 7 (Vengurla beach), and 8 (Aravali beach). Aravali Beach has a very low concentration of magnetic minerals, precluding realistic assessment of its seasonal accretion–erosion pattern. At Redi Beach (Stations 15–20), the concentration levels of magnetic minerals are high premonsoon, which further increases during monsoon season, although at certain locations the rise continues postmonsoon. The sediments of these three beaches have variable proportions of magnetite, titanomagnetite, and hematite. The concentration of magnetic minerals is more at the northern (Stations 1 and 2) and southern (Stations 16–19) ends of Vengurla and Redi beaches, respectively. The provenance of magnetite and titanomagnetite can be attributed to Deccan traps and relict sands.

This technique can complement the conventional methods and underlines the utility of magnetic parameters in studying sediment movement along the beaches.

ADDITIONAL INDEX WORDS: *Magnetic susceptibility, frequency-dependent susceptibility, magnetic minerals, beach sediments, ferrimagnets, Maharashtra, West Coast, India.*

INTRODUCTION

Sandy beaches are the functional links between the land and the sea and are affected by humans for their economic and recreational utility through tourism, fishery, ports, and urbanization. Sustainable management of beaches is thus becoming a major issue worldwide. The threat of coastal erosion and accretion is also a matter of concern for beachfront developers, property owners, and coastal planners. Hence, scrutiny of beach and coastline changes is fast becoming imperative.

The beach and nearshore zone is the most dynamic among the coastal environments; hence, studies on sediment transport and accumulation are of vital importance to projects such as dock construction and coastal reclamation (Crickmore *et al.,* 1990). To decipher the movement of sand in the beach and nearshore zone, various means ranging from mineralogical to radioactive have been attempted. But sand movement has been sparsely traced by harnessing magnetic properties or parameters of the beach material. Oldfield *et al.* (1979) and Walling *et al.* (1979) traced the suspended sediment sources in streams using natural magnetic enhancement known to occur in soils on a wide variety of substrates. Rummery *et al.* (1979a) tracked the downstream movement of magnetic minerals formed in soils. Arkell *et al.* (1982) and Rummery *et al.* (1979b) exhibited artificially how enhanced iron-rich streambed load could be suitably characterized to provide material for sediment tracing in fluvial systems. Shankar, Thompson, and Prakash (1996) used magnetic techniques to estimate heavy and opaque mineral contents of beach and offshore placers, while Hossain (1975) used magnetic susceptibility to characterize polyframboidal pyrite in beach sands to delineate its provenance. Recently, grains of sand have been tagged magnetically (Kuno *et al.,* 2003), while Hounslow and Morton (2004) evaluated sediment provenance using magnetic mineral inclusions in clastic sediments. Booth *et al.* (2005, 2008) have evaluated mineral magnetic concentration data as particle size proxies and have listed the correlations of magnetic susceptibility (χ_{LF}), susceptibility of anhysteretic remnant magnetization (χ_{ARM}), saturation isothermal remnant magnetization (SIRM), and percentage of frequency-dependent χ_{LF} and χ_{ARM} with different grain sizes.

The present study does not use any "active" or "passive" tracers; instead, spatial variation in terms of seasonal deposition (erosion) of beach is harnessed to trace out the variability and concentration of magnetic minerals for qualitative assessment of sediment movement. This technique,

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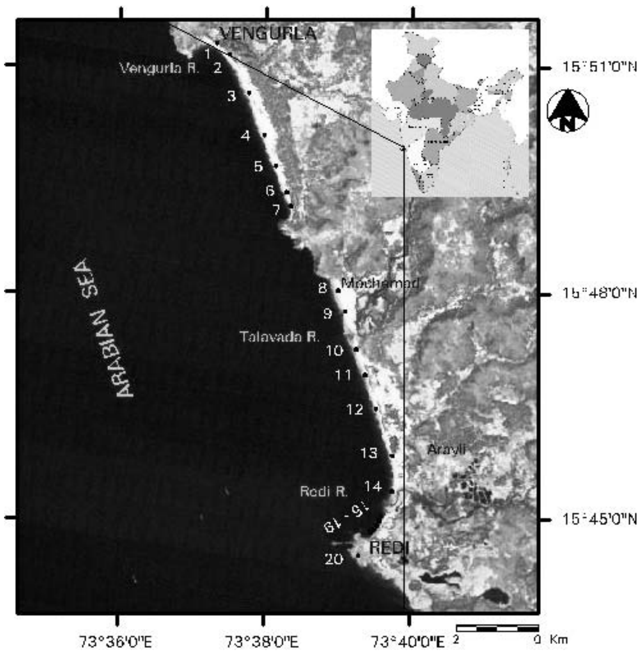

Figure 1. Location map of the study area showing the study sites.

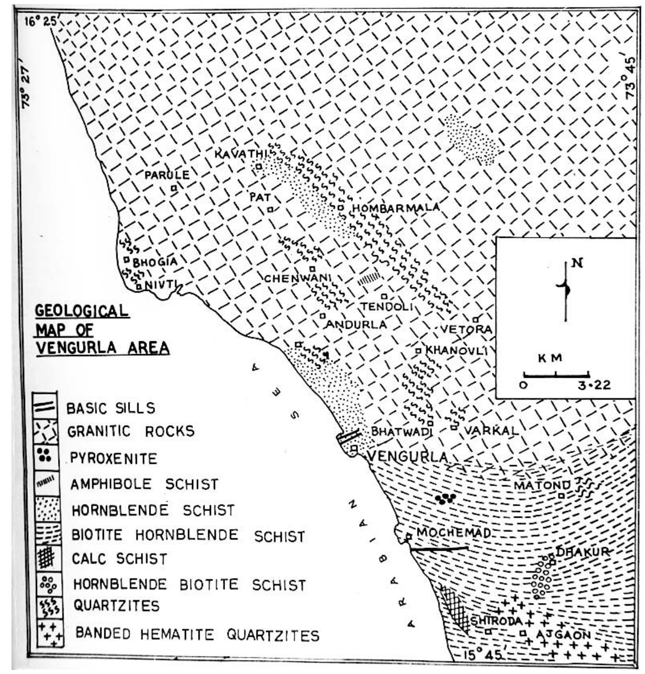

Figure 2. Geology of the area around Vengurla (Deendar, 2003).

being fast and cost effective, can complement the "traditional" methods used to study sedimentological variations in beach environments. Bulk samples require little time for preparation, and their individual magnetic susceptibility measurements, for example, do not take more than a minute to perform. The other aim of this study is to understand coastal dynamics to decipher depositional environment and provenance of beach sediments. The data can be used in modeling of coastal processes for coastal management.

STUDY AREA

The beaches between Vengurla and Redi stretch more than 12 km in length and are located in the Sindhudurg district, the southernmost part of the Maharashtra state (15°44′–15°52′ N, 73°35′–73°40′ E; Figure 1). These beaches are microtidal and are under the influence of semi-diurnal tides. They are a part of the Konkan Coast, which has morphological features distinct from those of the rest of the Indian coast (Chandramohan, Anand, and Nayak, 1992). The entire coastal stretch of Konkan was tectonically active during the Miocene–Pliocene period. Since then, exogenetic processes have been dominating (Tandale, 1993). The study area has three stretches of beach: Vengurla Beach (Vengurla-Kepadevi, Stations 1–7; width 30–150 m), Aravali Beach (Mochemad-Kerwada, Stations 8–14; width 50–185 m), and Redi Beach (Stations 15–20; consists of several pocket beaches with a length of ~300–500 m). The rainfall ranges between 300 and 470 cm/y, and wave height reaches up to 1.0 m, with an average wave period of 5 to 6 seconds. The predominant wave activity is of plunging type with multiple breakers.

The geology of the area (Figure 2) consists of banded hematite quartzite, varieties of schist, and granitic rocks (Deendar, 2003). Vengurla has a moderate to bold relief with hills and deep valleys. It has a coastline on its western side with a NNW–SSE trend. The coastline to the north of Vengurla is rocky, but it is not so in the south. River Karli flows from east to west and borders the northern part. River Talvada flows from north-east to south-west and joins the sea at Mochemad. River Redi, which marks the southern border of Vengurla, has a north–south flow on the eastern side and abruptly changes to and east–west direction near Shiroda to join the sea. The general trend of the major rivers in the area is from east to west, where they join the Arabian Sea. Two more rivers join the sea at the Vengurla port hill, situated on the northern and southern sides of the hill. These rivers have a major east–west trend. The important rock units in the region are banded hematite quartzite, quartzite, and schist (amphibolite and garnet), as well as granitic rocks. The area is structurally disturbed and influences the geology and the drainage pattern to a large extent (Deendar, 2003). Faulting is a major factor influencing the deformation and rock alterations, facilitating the formation of residual ore deposits and iron ore containing rocks in the area. The sustainable iron ore deposit of Redi, thus formed, has supported large-scale mining operations over a long period, with workable reserves of about 48 metric tons (Hiremath, 2003).

METHODOLOGY

The upper 3 to 4 cm of surface sediment samples were collected from the beaches every 10 m from a reference point, *i.e.,* 0 m (near the land), 10 m, 20 m, and so on (away from the land toward the sea), seasonally premonsoon (May 2003), during monsoon season (July 2003), and postmonsoon (November 2003) at 20 selected stations along beaches of the study area (Figure 1). Three types of magnetic measurement—χ_{LF}, IRM, and ARM—are used in the present study. All magnetic parameters were measured at the Environmental Magnetism Laboratory, Indian Institute of Geomagnetism, Navi Mumbai, India.

Magnetic susceptibility is related to total magnetic mineral concentration in the sediments and is a manifestation of detrital input and the subsequent dilution by diamagnetic and paramagnetic minerals. On dried samples, χ_{LF} was determined using a Bartington MS-2 magnetic susceptibility meter (with an alternating current magnetic field amplitude of 80 A/m) linked to an MS2B dual-frequency sensor (470 and 4700 Hz). The average of four measurements is presented as mass specific values in 10^{-7} m^3 kg^{-1}. It is customary to express ARM as anhysteretic susceptibility (χ_{ARM}; mass specific ARM/strength of the biasing field). It is expressed in 10^{-5} m^3 kg^{-1} and was induced onto select samples from a few stations. This parameter is sensitive to concentration, as well as grain size, of ferrimagnetic minerals in a sample. For example, χ_{ARM} is highly selective of single-domain (SD) ferrimagnetic grains in the 0.02 to 0.4 μm range (King *et al.,* 1982; Maher, 1988). With ferrimagnetic grain sizes both above and below this range, χ_{ARM} values drop quite dramatically (Walden, Oldfield, and Smith, 1999).

Acquisition of IRM was carried out using a Molspin pulse magnetizer, and remanences were measured by a Molspin spinner magnetometer. Saturation isothermal remanent magnetization (SIRM) was imparted using a maximum field of 1 T. SIRM is measured on a mass specific basis (expressed in 10^{-5} Am^2 kg^{-1} SI units) and is influenced by concentration of all remanence-carrying minerals in the sample. But the value also strongly depends upon the assemblage of mineral types and their magnetic grain size (Walden, Oldfield, and Smith, 1999).

Magnetic data, when expressed as interparametric ratios, provide information on changing magnetic grain size or changing chemistry. Ratios used here are χ_{ARM}/χ_{LF}, SIRM/χ_{LF}, and χ_{ARM}/SIRM. A general fining of magnetic grain size is seen to produce an increase in those ratios with χ_{ARM} as the numerator, provided the reduction in grain size does not shift the distribution dominantly into SP region. In the latter case, an increase in relative contribution of SP grains reduces those ratios that have χ_{LF} as the denominator. Here, the χ_{ARM}/SIRM quotient is useful, since it responds to changes in only those grain sizes that lie above the SP boundary. Opposite trends in χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM may therefore indicate that changes in the ultrafine component have produced a relative change in SP to SSD contributions.

More detailed explanations on the preceding parameters and their measurement can be found in Basavaiah and Khadkikar (2004), O'Reilly (1984), Thompson and Oldfield (1986), and Walden, Oldfield, and Smith (1999).

RESULTS AND DISCUSSION

Vengurla Beach

Station 1

Premonsoon χ_{LF} at Station 1 (Figure 3) is 2 to 6 ($\times$ 10^{-7} m^3 kg^{-1}), between 0 and 30 m, from which it gradually decreases and is lowest at 90 m (0.79). At the same locations, during monsoon, χ_{LF} is considerably high at 0 m (31.89); low to moderate at 10, 20, and 30 m (4.02, 5.43, and 13.27, respectively); and lowest beyond 30 m and up to 60 m (1.64 and 1.45, respectively). The postmonsoon χ_{LF} values show a coarse inverse relationship with the premonsoon trend and are low at 10, 20, and 50 m, beyond which they are very low.

Furthermore, to characterize the magnetic grain size of the magnetic minerals, ARM and SIRM was carried out on a few samples. For Station 1, the values are presented in Table 1; their ratios are in Table 2. As seen from Table 1, χ_{ARM} values indicate that at this station samples contain high to moderate concentrations of SD ferrimagnets premonsoon; moderate to very low concentrations in monsoon season; and low to very low concentrations postmonsoon. SIRM values show variations similar to those of χ_{LF}, and the samples at this station contain high to moderate concentrations of all remanence-carrying magnetic minerals premonsoon; very low concentrations in monsoon season; and moderate to very low concentrations postmonsoon.

Interparametric ratios are useful for sample discrimination in studies of sediments with mixed provenance as they remove masking effects of the concentration of magnetic minerals on bulk sediment magnetic properties, permitting evaluation of other controls, such as mineral type and the grain sizes of ferrimagnetic components (Lees, 1999). Ratios of χ_{ARM}/χ_{LF}, χ_{ARM}/SIRM, and SIRM/χ_{LF} are shown in Table 2. Ratios of χ_{ARM}/χ_{LF} and SIRM/χ_{LF} indicate moderate to high concentrations of magnetic grains in the fine SD range premonsoon; moderate to low concentrations during monsoon season; and low concentrations postmonsoon. The χ_{ARM}/SIRM ratio denotes that selective loss of finer grains is less premonsoon; high to low in monsoon season; and low postmonsoon.

Station 2

At Station 2, the premonsoon χ_{LF} (Figure 3) ranges from 0 to 4, which is highest at 20 m (3.73) and lowest at 70 m (0). A marginal increase is seen in monsoon season, wherein at 20 m χ_{LF} is highest (10), gradually decreases to 5 at 40 m, and tapers off to 1 at 80 m. In postmonsoon samples, χ_{LF} further decreases to 2 at 0 m, which increases at 10 m (4) and 20 m (8). From 30 to 90 m, the values are uniform, around 1.

Station 3

At Station 3, for all three seasons, χ_{LF} is uniformly low (Figure 3), with a tiny increase during monsoon season from 10 to 30 m. A slight decrease occurs postmonsoon, where the highest χ_{LF} (6) is seen at 10 m. To identify the actual magnetic minerals present along the beaches, stepwise thermal demagnetization of SIRM was carried out on select samples. The demagnetization of samples collected at Station 3, 0 m, postmonsoon and premonsoon display a distinct change in behavior from 200 to 400°C (Figure 4). A drop in SIRM occurs in the postmonsoon sample at 250°C, after which a gradual decrease is seen to about 675°C. This could be due to titanomagnetite and hematite. The premonsoon sample has one magnetic mineral phases with unblocking temperature

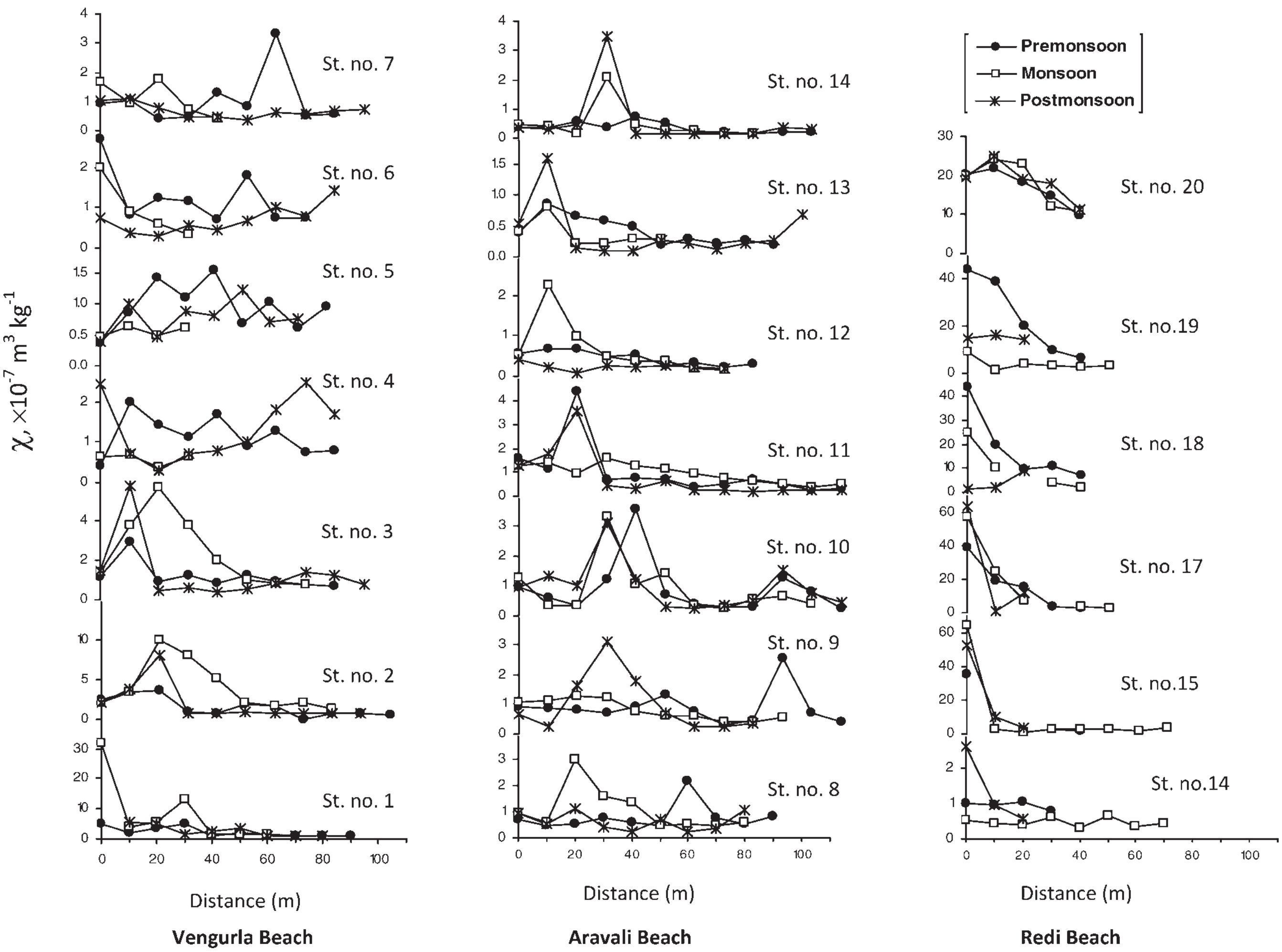

Figure 3. Seasonal variation in magnetic susceptibility along the three beaches: (1) Vengurla, (2) Aravali, and (3) Redi.

(T_b) of about 400°C, denoting the presence of titanomagnetite, and the other is magnetite with a T_c of about 580°C.

Station 4

Station 4 is characterized by the presence of very low χ_{LF} (0–2; Figure 3). Values of χ_{ARM} listed in Table 3 indicate that at this station samples contain low to moderate concentrations of SD ferrimagnets premonsoon and very low concentrations in both monsoon and postmonsoon periods. SIRM values (Table 3) indicate samples contain low to moderate concentrations of all remanence-carrying magnetic minerals premonsoon; very low in monsoon and postmonsoon periods.

Ratios of χ_{ARM}/χ_{LF} and SIRM/χ_{LF} (Table 4) indicate moderate to high concentrations of magnetic grains in the fine SD range premonsoon and during monsoon and low concentrations postmonsoon. The χ_{ARM}/SIRM ratio denotes that the selective loss of finer grains is lower in all three seasons.

Samples collected at this station at 0 m during the monsoon and postmonsoon campaigns display a spectra of decrease in

Table 1. *χ_{ARM} and SIRM values for Station 1.*

Distance Seaward	Premonsoon		Monsoon		Postmonsoon	
	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})
0 m	1.0	8056	0.64	53	0.10	819
30 m			0.18	170		
50 m	0.3	2812			0.07	504
60 m			0.03	176		
80 m					0.03	119
90 m	0.3	1116				

Table 2. *Ratios of χ_{ARM}/χ_{LF}, χ_{ARM}/SIRM and SIRM/χ_{LF} for Station 1.*

	Premonsoon			Monsoon			Postmonsoon		
Distance Seaward	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM ($10^{-4}A^{-1}m$)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM ($10^{-4}A^{-1}m$)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM ($10^{-4}A^{-1}m$)	SIRM/χ_{LF} (κAm^{-1})
0 m	21.4	1.29	165.4	1.99	120.3	0.17	1.88	1.25	15.1
30 m				1.34	10.4	1.3			
50 m	15.8	1.20	131.4				1.86	1.37	13.6
60 m				2.21	1.8	12.2			
80 m							2.70	2.14	12.6
90 m	35.8	2.52	142						

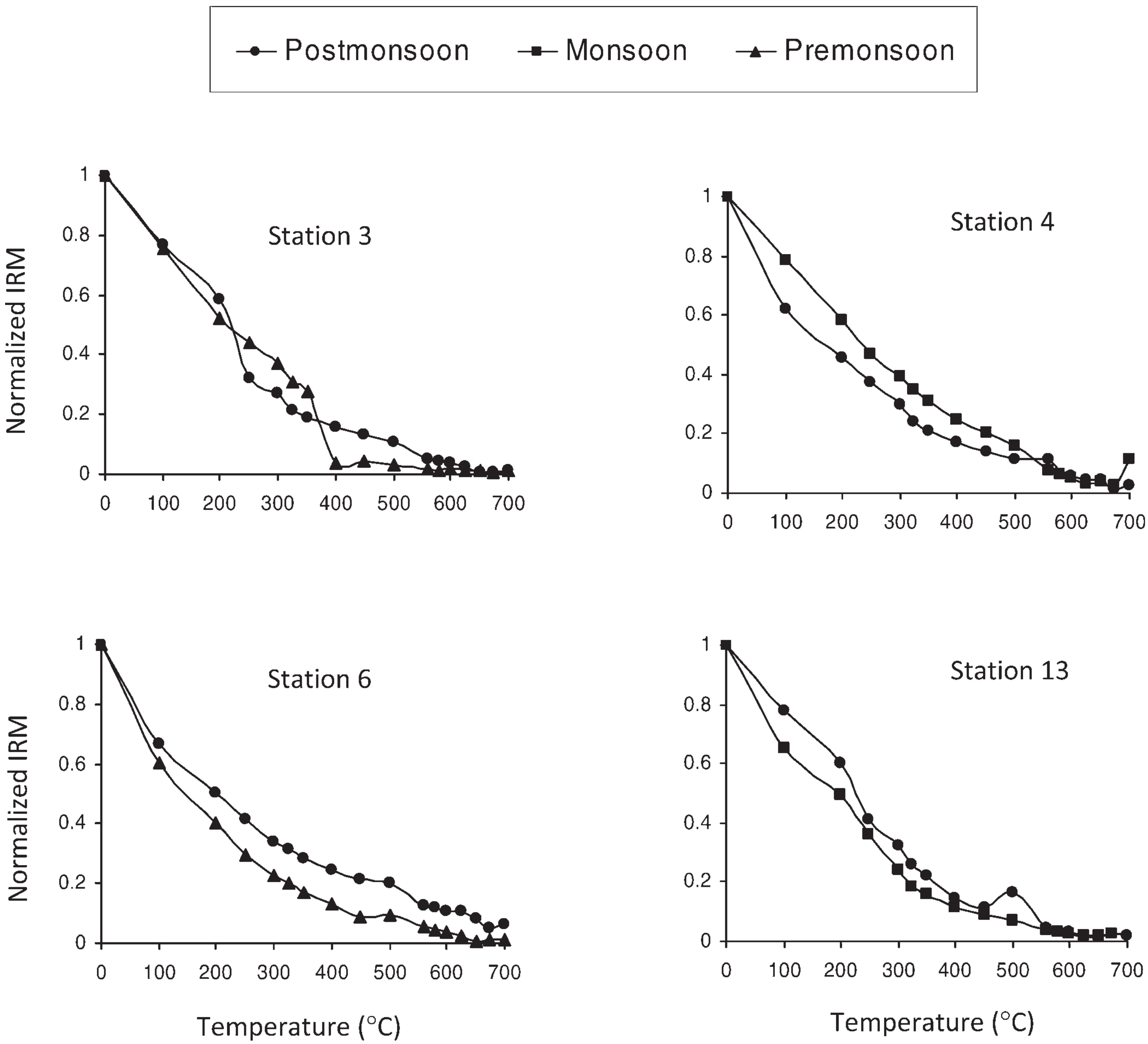

Figure 4. Thermal demagnetization studies on select beach samples.

Table 3. *χ_{ARM} and SIRM values for Station 4.*

Distance Seaward	Premonsoon χ_{ARM} (10^{-5} m^3 kg^{-1})	Premonsoon SIRM (10^{-5} Am^2 kg^{-1})	Monsoon χ_{ARM} (10^{-5} m^3 kg^{-1})	Monsoon SIRM (10^{-5} Am^2 kg^{-1})	Postmonsoon χ_{ARM} (10^{-5} m^3 kg^{-1})	Postmonsoon SIRM (10^{-5} Am^2 kg^{-1})
0 m	0.1	567	0.01	69	0.04	339
30 m			0.02	83		
40 m	0.3	2382				
50 m					0.02	109
80 m	0.2	1186				
90 m					0.03	227

SIRM, with temperature reaching a T_b of about 300°C, 580°C, and 680°C (Figure 4), indicating titanomagnetite, magnetite and hematite, respectively.

Stations 5 and 6

At Stations 5 and 6, very low χ_{LF}, are seen for all the three seasons (0.–2 for station 5 and 1–3 for station 6; Figure 3). Thus, wide variation occurs in this parameter signaling the scant presence of magnetic minerals. On demagnetization, the 0-m sample collected in monsoon season at Station 6 shows a T_b of around 450°C and 675°C (Figure 4), denoting the presence of titanomagnetite and hematite, respectively.

Station 7

The trend of very low χ_{LF} (Figure 3) started at Station 4 continues at Station 7 (0–3). Values of χ_{ARM} displayed in Table 5 indicate that at this station samples contain low concentrations of SD ferrimagnets premonsoon and very low concentrations in monsoon and postmonsoon periods. SIRM values (Table 5) indicate samples contain moderate (0 m premonsoon) to very low concentrations of all remanence-carrying magnetic minerals during all three seasons.

Ratios of χ_{ARM}/χ_{LF} and SIRM/χ_{LF} (Table 6) indicate moderate concentrations of magnetic grains in the fine SD range premonsoon and low concentrations in monsoon and postmonsoon periods. The χ_{ARM}/SIRM ratio denotes that selective loss of finer grains is low to moderate premonsoon, whereas it is low in monsoon and postmonsoon periods.

Aravali Beach (Stations 8 to 14)

Station 8

Like the previous few stations of Vengurla Beach, very low χ_{LF} prevails at Station 8 (0–2, Figure 3). Values of χ_{ARM} displayed in Table 7 indicate samples contain low concentrations of SD ferrimagnets premonsoon and very low concentrations in monsoon and even postmonsoon periods. SIRM values (Table 5) indicate samples contain very low concentrations of all remanence-carrying magnetic minerals during all three seasons.

Ratios of χ_{ARM}/χ_{LF} and SIRM/χ_{LF} (Table 8) indicate moderate to low concentrations of magnetic grains in the fine SD range premonsoon, during monsoon, and postmonsoon. The χ_{ARM}/SIRM ratio denotes that loss of finer grains is moderate premonsoon, whereas it is low in monsoon and postmonsoon periods.

Stations 9 to 14

The trend of low χ_{LF} (0.–4) is seen to prevail throughout this beach spanning all its remaining stations (Figure 3) signifying the scantiness of magnetic minerals.

The sample collected at Station 13, 0 m, during monsoon season is seen to display two phases of magnetic mineralogy (Figure 4), one with a T_b at 420°C (titanomagnetite) and the other with a T_b that lies between 580 and 600°C. This could be magnetite. The postmonsoon sample at Station 13, 0 m, displays a T_b of 580°C, *i.e.,* magnetite (Figure 4).

Redi Beach (Stations 15 to 20)

Stations 15 and 16

Very low χ_{LF} is seen at Station 15 for all three seasons (Figure 3). At Station 16, however, a reversal is seen wherein for a 0-m sample χ_{LF} is 35.41 premonsoon, almost doubles (64.17) for the same sample location during monsoon season, and decreases marginally to 52.30 postmonsoon (Figure 3). During monsoon season from 10 to 70 m, χ_{LF} is low and not too variable (1.28 to 3.69). It increases postmonsoon at 10 and 20 m and is highest at 0 m (52.30).

Table 4. *Ratios of χ_{ARM}/χ_{LF}, χ_{ARM}/SIRM and SIRM/χ_{LF} for Station 4.*

Distance Seaward	Premonsoon χ_{ARM}/χ_{LF}	Premonsoon χ_{ARM}/SIRM (10^{-4}A^{-1}m)	Premonsoon SIRM/χ_{LF} (κAm^{-1})	Monsoon χ_{ARM}/χ_{LF}	Monsoon χ_{ARM}/SIRM (10^{-4}A^{-1}m)	Monsoon SIRM/χ_{LF} (κAm^{-1})	Postmonsoon χ_{ARM}/χ_{LF}	Postmonsoon χ_{ARM}/SIRM (10^{-4}A^{-1}m)	Postmonsoon SIRM/χ_{LF} (κAm^{-1})
0 m	29.4	2.1	137.5	2.3	2.1	10.9	1.6	1.1	13.8
30 m				2.2	1.7	12.7			
40 m	18.1	1.3	140.9						
50 m							1.9	1.4	13.5
80 m	21.4	1.5	146.7						
90 m							1.8	1.3	13.4

Table 5. χ_{ARM} *and SIRM values for Station 7.*

Distance Seaward	Premonsoon		Monsoon		Postmonsoon	
	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})
0 m	0.2	1500	0.03	241	0.02	147
20 m			0.03	169		
40 m	0.2	1851	0.01	42		
50 m					0.01	62
80 m	0.1	80				
90 m					0.02	96

Station 17

At Station 17, χ_{LF} continues to be on the rise. Premonsoon, χ_{LF} is maximum (Figure 3) at 0 m (38.73) and abruptly decreases to 18.78 and 15.74, respectively, at 10 and 20 m. Again, an almost sudden fall occurs at 30 m (3.36) and 40 m (2.91). However, during monsoon season, as compared to premonsoon season, χ_{LF} is more at 0 m (57.01) than at 10 m (24.67). At 20 m (7.09), 40 m (3.19), and 50 m (2.30), it is considerably low. Postmonsoon χ_{LF} is quite variable: 63.59 (at 0 m), 1.25 (at 10 m), and 11.72 (at 20 m).

Station 18

At Station 18, χ_{LF} is quite high (Figure 3), especially at 10 m (43.89) premonsoon. But unlike other stations, here χ_{LF} decreases during monsoon season, albeit marginally, at 10 m (24.69) and 20 m (10.40). Postmonsoon, it drastically comes down at 10 m (1.09) and 20 m (1.80), increasing a bit at 30 m (9.10).

Station 19

Premonsoon χ_{LF} values are high at 10- and 20-m (44.37 and 39.1, respectively) sampling locations (Figure 3) that gradually decrease to 6.25 at a 50-m sampling site. During monsoon season, however, a sharp drop occurs in χ_{LF} at all sampling sites. Postmonsoon χ_{LF} seems enhanced, hovering around 15 between 10 and 30 m.

Station 20

Station 20 is characterized by high χ_{LF} values (Figure 3) from 0 to 20 m (also 30 m postmonsoon) during all three seasons. These values range from 10 to 25, whereas the rest of the sampling locations have less χ_{LF}.

Summary

At Vengurla beach (Stations 1–7), magnetic minerals are moderately present between 0 and 30 m premonsoon at Station 1, beyond which they are low to lowest. At the same locations, high concentrations are evident in monsoon season, while at the remaining locations they are moderate to very low. Furthermore, their concentration is low to very low concentrations postmonsoon at all sampling locations. At station 2, magnetic minerals are low to very low premonsoon. However, an increase is seen in their concentration during monsoon season and is more at 20 and 30 m. Still, for corresponding locations postmonsoon, the decrease in magnetic minerals is appreciable at 30 m and remains the same or unchanged at 20 m. At all other locations, the mineral magnetic concentration is considerably low postmonsoon.

The stretch from stations 3 to 7 has very low concentration of magnetic minerals. The concentration of SD ferrimagnets at stations 1, 4, and 7 ranges from high to very low. Magnetite, titanomagnetite and hematite are present at stations 3, 4, and 6. Aravali beach (Stations 8–14) has meager quantity of magnetic minerals at all its stations and at all of its sampling locations. At station 8 low to very low concentration of SD ferrimagnets is present in all the three seasons. Titanomagnetite and magnetite is present at station 13. At Redi Beach (Stations 15–20), the concentration levels of magnetic minerals increase considerably from Station 16 onward, especially at 0 m. Station 17 is characterized by a higher concentration of magnetic minerals premonsoon, which is still higher in monsoon season and highest at 0 m postmonsoon. However, at other places, the concentration decreases postmonsoon. At this station, the single- or multidomain and coarse-grained ferrimagnetic particles are quite in excess. The concentration at stations 18, 19, and 20 is high premonsoon, moderate in monsoon season, and very low postmonsoon. Thus, high χ_{LF},

Table 6. *Ratios of* χ_{ARM}/χ_{LF}*,* χ_{ARM}*/SIRM and SIRM/*χ_{LF} *for Station 7.*

Distance Seaward	Premonsoon			Monsoon			Postmonsoon		
	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})
0 m	22.0	1.4	157.3	2.2	1.5	14.6	2.2	1.5	14.3
20 m				1.8	1.9	9.5			
40 m	18.2	1.3	141.8	3.6	3.4	10.6			
50 m							3.7	2.0	17.8
80 m	24.6	17.0	14.4						
90 m							2.4	1.8	13.5

Table 7. *χ_{ARM} and SIRM values for Station 8.*

Distance Seaward	Premonsoon		Monsoon		Postmonsoon	
	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χ_{ARM} (10^{-5} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})
0 m	0.12	85	0.01	99	0.02	107
40 m			0.02	142	0.01	30
70 m	0.27	261				
90 m	0.13	80	0.01	70	0.02	119

especially at Vengurla and Redi beaches, seem to be controlled by ferrimagnetic minerals like magnetite and titanomagnetite and to a lesser degree by antiferromagnetic minerals like hematite. Gujar *et al.* (2007) studied heavy mineral placers from Vijaydurg to Redi and found opaques to contain ilmenite, magnetite, and chromite, wherein magnetites are of two types-titanomagnetite and magnetite. Beach sediments at stations 1, 4, 7, and 8, show a seaward coarsening trend. This is because the point just seaward of low water level or backwash or breaker level is the place of maximum turbulence and the high-energy zone due to wave energy (Bascom, 1951; King, 1972). Hydrodynamic processes are an important source of placer formations along the beaches (Kurian *et al.,* 2000), as well as through alongshore and cross-shore movement of sediments (Chandrasekar *et al.,* 2003). 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. Also, the heavy mineral concentration is not just linked to the source but 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 are claimed to influence grain size characters and mineralogical composition (Chavadi and Hegde, 1989). In the direction of transport, the 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 removes finer particles and leaves 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 heavies to be associated with the erosional profile, indicating the concentration of heavies is more by the strong winnowing action of waves and less by the selective transport through alongshore currents.

The concentration of magnetic minerals is more at the northern (Stations 1 and 2) and southern (Stations 16 to 19) ends of Vengurla and Redi beaches, respectively, possibly due to sediments being dispersed directly under the influence of waves and alongshore currents. Heavy minerals, depending upon their specific gravity, size, and shape, do not settle in a high-energy turbulent environment; instead, they drift farther on either side along the coast (May, 1973). 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 wave energy.

PROVENANCE

The heavy mineral placers along the Konkan Coast are enriched in ilmenite and magnetite, along with granitic and metamorphic index–heavy 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, Figure 5) 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 coarse-grained garnet mineral in the schist rocks (garnet schist).

Heavy mineral studies have been carried out along the Karnataka Coast to delineate the provenance of beach sands (*e.g.,* Hanamgond, Gawali, and Chavadi, 1999; Hegde, Shalini, and Kanchanagouri, 2006). A suite of opaques, hornblende, pyroxene, and rutile suggest a silicic igneous source (Friedman and Sanders, 1978; Pettijohn, 1975). The presence of rounded rutile, rounded tourmaline, and rounded zircon suggests the source to be gneisses, schists, and other such highly metamorphic rocks. Green hornblende, epidote, sphene, zircon, ilmenite, and magnetite in the heavy mineral suite are indicative of granitic, gneissic, and basic sources (Hegde, Shalini, and Kanchanagouri, 2006). However, the presence of minerals like garnet, kyanite, and staurolite suggests a high-grade metamorphic source, whereas altered-rounded ilmenite suggests

Table 8. *Ratios of χ_{ARM}/χ_{LF}, χ_{ARM}/SIRM and SIRM/χ_{LF} for Station 8.*

Distance Seaward	Premonsoon			Monsoon			Postmonsoon		
	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})	χ_{ARM}/χ_{LF}	χ_{ARM}/SIRM (10^{-4}A^{-1}m)	SIRM/χ_{LF} (κAm^{-1})
0 m	16.6	14.1	11.8	1.5	1.4	10.5	1.6	1.4	11.5
40 m				1.2	1.2	10.3	3.6	2.9	12.4
70 m	33.6	10.2	33.1						
90 m	16.3	16.6	9.8	2.1	1.8	11.7	1.4	1.3	10.9

Figure 5. Field photograph showing black sand deposit along eastern stretch of Redi beach.

reworked older ilmenite. A comprehensive review on provenance analysis is given by Weltje and Eynatten (2004). Nevertheless, it is quite possible, based upon a suite of assemblage of heavy minerals present, to assign an erroneous source to beach sands. Magnetic mineral studies carried out in this instance prove the point. It is expected that the beaches under study receive their detrital input from the surrounding region, which is dominated by the presence of hematitic mineral assemblage in the country rock. The beaches, on the contrary, contain a smaller amount of hematite. They are dominated by the presence of a ferrimagnetic assemblage like magnetite and titanomagnetite. This scenario gives rise to two possibilities. The first possibility pertains to transformation of hematite to magnetite, which can be overlooked because of a lack of high temperature and anaerobia (Schwertmann and Fechter, 1984; Tunstall *et al.,* 1976). The possibility of neoformation of magnetite under ambient soil-forming conditions can also be discounted (Taylor *et al.,* 1987). The second likelihood envisaged for the presence of magnetite across these beaches is that they have come from the Deccan traps and relict sands, which are available, offshore, from Holocene sediments through alongshore currents. Magnetic minerals are concentrated more during monsoon, especially at the Vengurla and Redi stretch, mainly due to selective removal and accumulation of heavy minerals and winnowing of light material seaward because of a high-energy condition. Furthermore, the overall high concentration of magnetic minerals at Redi Beach can be attributed to the availability of iron ore deposits (banded hematite quartzite and hematite), mining dumps stacked right above the beach (Figure 6), and spilling during the transportation through 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 lensoid bodies. It is also possible that, since the Redi headland is separated by River Redi in the north and River Terekhol in the south, this configuration may not allow the minerals to be redistributed along its northern and southern sectors.

Figure 6. Field photograph showing iron ore dump and black sand deposit along western stretch of Redi beach.

CONCLUSIONS

Vengurla and Redi beaches have seasonally variable concentration of magnetic minerals, which is high during monsoon than premonsoon and postmonsoon, though at certain locations at Redi beach it is seen to increase further postmonsoon. At Aravali beach the concentration of magnetic minerals is very low making it difficult to discern any seasonal trend. Magnetic minerals are more at the northern (Stations 1 and 2) and southern (Stations 16 to 19) ends of Vengurla and Redi beaches, respectively. Fine SD grains are more premonsoon, than during monsoon and postmonsoon at Stations 1, 4, 7, and 8. Magnetite, titanomagnetite and hematite were identified at Stations 3, 4, 6 and 13. The presence of magnetite and titanomagnetite can be attributed to Deccan traps and relict sands.

The present study underlines the utility of magnetic parameters in studying sediment accumulation and erosion (movement) along the beaches since it allows rapid and reliable collection of the initial data on sand movement.

This technique, being fast and cost effective, can complement the "traditional" methods used to study sedimentological variations in beach environments.

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