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An Overview of Late Quaternary Studies and Status of Mineral Magnetism from the Konkan Coast: Constrains on Degradation of the West Coast of India

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Abstract

We present here an overview of textural, sedimentological, magnetic, and remote sensing studies from different sectors of the west coast along with new mineral magnetic results. The emerging coastal erosion and growing incidences of extreme events with an increase in cyclones in the Arabian Sea are affecting these beaches at higher rates of dynamics. The sand characteristics, textures, sorting and clast composition have been studied to correlate them with energy conditions and interpret the transportation dynamics. Heavy mineral analyses delineated provenances and detrital pathways, the morphological and volumetric vicissitudes of beaches helped characterize western coast beaches into stable, eroding or depositing regimes aided by time elapsed satellite images. The multi-parametric studies unravel the relationship of hydrodynamics over a range of geomorphic features. The predominant controls of longshore and rip currents in altering the land-sea interfaces at less than decadal scales were observed.

New mineral magnetic results from the Vengurla Beach of the Sindhudurg district are evaluated in above context and to establish semiquantitative relations amongst depositional and erosional patterns that can be further linked to the effects of degree and intensity of local monsoon. The beaches record systematic changes in the concentration of magnetite, haematite, maghaemite, and goethite as a result of a combination of the above beach processes. The studies from Vengurla beach successfully demonstrate mineral magnetism as a suitable quantitative approach to depict the quasi-decadal effects of long shore currents that are further governed by the shoreline changes resultant of increasing competitiveness between coastal erosion and depositional conditions in recent years. The status of studies over the west coast depicted an alarming increase in the rates of erosion at several beaches demanding quantitative monitoring using the integrative approach of mineral magnetism and satellite data.

Keywords: West Coast, Magnetic Susceptibility, Curie Temperature, Provenance, Sindhudurg.

Introduction

The factors responsible for beach morphological and sedimentological changes have largely been natural in the geological past. However, in the recent past the *anthropogenic constraints have* become pertinent all over the world to affect the coastal environments. Unraveling of these processes is likely to reveal mitigation measures to lower down the deleterious human impact on the beaches. Also, an understanding is increasing about the linkages between tectonics and climate. The sea level changes along with monsoonal variability have great influence on accumulation/erosion over the beaches in Indian context. The beach sands offer clues to the provenance and hence their study is quite important to understand the detrital pathways and the physicochemical domain of the source and sink.

Beach sediments have been used to decipher detrital and sedimentary pathways, their composition, grain size, provenance, characteristics and their interrelationship between different parameters (Kasper-Zubillaga and Dickinson, 2001; DiGiulio *et al.,* 2003; Hanamgond and Chavadi, 1992, 1993; Hanamgond *et al.*, 1999). But, the relation between different parameters is always not so straight forward and some ambiguities do creep in. The coastal sands do not always project the accurate composition of their source (Kasper-Zubillaga and Carranza-Edwards, 2005).The present attempt is aimed at understanding the significance of beaches in unraveling geological processes and activities along the west coast with the special emphasis on the Konkan Coast (Fig. 1).

Another objective is also to summarize research carried to understand the west coast dynamical changes. The diurnal and seasonal changes impact beach morphology. The beach

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Fig. 1. Location of the study area along west coast of India. Samples are collected from Vengurla (array 1 to 7) beach.

characterization is done by performing sedimentological and textural studies, apart from beach profiling and volume change studies. These techniques are time consuming, labor intensive, and rigorous. Recently, two more methods of great utility have been added to this pantheon, and they are magnetic measurements and remote sensing. Remote Sensing and GIS provide fast and robust estimates of erosion/accretion over a period of time and is also helpful in comprehending near shore and beach processes. The coasts, in general, are productive economically and recreationally and any shoreline change can impact it adversely.

The endeavor of this study is also to ascertain the magnetic concentration along beach of Sindhudurg-Vengurla and how it varies with time and space. The factors responsible for this variability will also be probed and provenance of the magnetic minerals deciphered. To tackle coastline changes in an effective manner comprehensive understanding of the key processes that influence these changes is needed so that the ecosystem management and human decision-making to deal with coastal change becomes easy and effective. This will require building a broad database culled from different sources.

An Overview of Five Decades of Geoscientific Studies in the West Coast

Influence of Sea-level Fluctuations and Tectonics on Erosion and Depositional Regimes

Multiple transgression-regression episodes along Maharashtra coast were radiometrically cataloged by Kale *et al.* (1984) revealing sea level was low from 30to 35 ka BP, rose after 30 ka BP, regressed again, rose back at around 15 ka BP and was maximum close to mid-Holocene. The sea level has remained steady from 6 ka BP to the present, though a rise of 1-6 m was inferred in the period from 6 ka to 2 ka BP. Pandarinath *et al.* (2001) inferred low Arabian sea level during Late Pleistocene-Early Holocene (10760 ± 130 to 9280 ±150 yr BP), transgression in Late Holocene, which receded and stabilized to present levels after 6400 yr BP. Isotopic measurements on beach rock carbonates from Devgad to Guhagar (Konkan) by Kumar *et al.* (2000) revealed their formation age ranged from 1100 to 3130 yr BP and they cemented in shallow vadose region under moderate temperature. Bhatt and Bhonde (2006) also identified two major palaeostrands based on geomorphic marine notches associated with late Quaternary sea-level changes along the Saurashtra coast.

The deposition of >40 ka BP Velas lignite beds (Konkan) situated presently ~100m away from msl suggests neotectonic activity (Rajshekhar and Kumaran, 1998). Deswandikar and Karlekar (1996) consider dune complex (Dive Agar, Konkan) formed 2k to 4k years back. Cliff height, erosion rate and slope angle at low and high tide was used to model shore platform (Kamble and Jog, 1996). Karlekar (2009) succinctly summarized sea-level records pertaining to Konkan coast. Karlekar (2001) opined relative chronology of Konkan sea-level changes is not comprehensive. The coastal region of Maharashtra was tectonically active in Miocene and Pliocene periods having quite vigorous exogenetic processes (Rajshekhar and Kumaran, 1998). Recently, with the development of remote sensing techniques, Konkan coast and beaches have been scrutinized closely and at a regional scale (Kunte and Wagle, 1993, 1994). The presence of the three generation of spit complexes along the Karnataka coast suggests the reversal of longshore currents thrice (Kunte and Wagle, 1991). Hanamgond and Mitra (2008) unraveled the construction of Malvan city has been on beach ridges, which formed in two phases as a result of tombolo effect.

Factors for Changes in West Coast Beach Morphology and Variable Sedimentation-Erosion Rates

Kunte and Wagle (2001) reviewed work on littoral transport along the west coast of India. It revealed littoral drift is variable, bi-directional, and seasonal, with long term southward drift along the west coast. Sreeja *et al.* (2016) identified 33 major rivers originate and 10 estuary complexes exist in the Western Ghats, wherein 132 drainage meet the Arabian sea through 23 major estuaries along 840 km coastal stretch of Maharashtra-Goa. The Konkan coastline has undergone multiple episodes of change in its physical landscape due to geotectonic processes like coastal subsidence and erosion/deposition, hinterland weathering and erosion, impact of regional fluvial systems(flooding) and their avulsion, storms, and cyclones as well as large scale changes in monsoon (Ahammed and Pandey, 2019). These processes and the population rise have led to changing land use which is impacting the coastline over a range of temporal scales. The factors responsible for changing the coastline pertain to sea level fluctuations (Bhattacharya, 2021; Das *et al.*, 2017; Vishnu *et al.*, 2017), continental mass upliftment or subsidence, river detrital input, submergence of sand ridges (Wagle and Veerayya, 1996), sediment distribution and redistribution (Kulkarni *et al.*, 2015; Venkatramanan *et al.*, 2011), placer minerals (Mallik, 1986), grain size distribution and wave energy (Sathasivam *et al.*, 2015), radioactivity (Mohanty *et al.*, 2003, 2004), storm surges and tsunami (Morner, 2004; Karikalan *et al.*, 2001; Singarasubramanian *et al.*, 2006, 2009; Narayan *et al.*, 2005), erosion hotspots (Noujas and Thomas, 2015; Srinivasalu *et al.*, 2007), dune formation and settlement (Kunz *et al.*, 2010), nearshore sediment characteristics (Narayana *et al.*, 2008), impact of mud banks on coastal dynamics (Parvathy *et al.*, 2015), evolution of coastal wetland systems (Padmalal *et al.*, 2011), sediment erosion/deposition in microtidal coasts (Kumar *et al.*, 2015; Dora *et al.*, 2014), and artificial structures constructed at the sea front like dykes and groynes (Mohanty *et al.*, 2012; Sathasivam *et al.*, 2015).

The modern coastal issues are related to coral mining, mangrove loss, sand dredging, sandbar/spit formation, soil and silt dam formation across rivers lowering the detrital input to sea and beaches (Kankara *et al.*, 2018). The maritime structure construction increases/decreases erosion. The width of Chennai's Marina beach increased after 1876 when harbor protection measures were adopted (Mani, 2001). Mining for placer monazite and ilmenite destroyed scores of beaches in states like Kerala and Karnataka. Salinity ingression is also on the rise in coastal aquifers (Prusty and Farooq, 2020; Prusty *et al.*, 2020; Vengadesan and Lakshmanan, 2019; Kanagraj *et al.*, 2018; Nair *et al.*, 2016, 2013; Sylus and Ramesh, 2015; Gupta *et al.*, 2010; Kumar, 2006).

Chandramohan *et al.* (2001) and Parry *et al.* (2007) infer a rise in coastal flood episodes as well as salinity increase. The estimated sea level rise for the 20th century was about 1.7 mm/yr (Bindoff *et al.*, 2007), though it did not change uniformly over decadal periods. Unnikrishnan *et al.*, (2006) estimated sea level rise from 1878 to 1994 to be 0.78 mm/yr for Mumbai; for Kochi from 1939 to 1997 it was 1.14 mm/yr; and from 1939 to 1994 it was 0.75 mm/yr at Visakhapatnam. They also inferred reversed trend for Chennai where the level dropped by 0.65 mm/yr from 1955 to 1994. A few notable studies on local sea level changes have been carried out by some workers (Unnikrishnan and Shankar, 2007; Nandy and Bandopadhyay, 2011; Kumar and Jayappa, 2009). Nayak *et al.* (2013) delineated about 35 km^2 Indian coastline which was inundated in the 20th century, of which about 4 m along with Mumbai, 8 m along with Kochi, and 7 m at Visakhapatnam coastline were seen to have shifted landward; and about 4 m seaward shift occurred at Chennai.

From 1984 to 2016, Luijendijk *et al.* (2018) found worlds 24% of sandy beaches are eroding, 20% are accreting and 40% are stable, whereas Rajawat *et al.* (2015) found 45.5% of Indian coasts were eroding, 35.7% accreting and 18.8% were stable for the time period from 1989-1991 and 2004-2006. During this time frame, they found erosion was slightly more than deposition along Maharashtra coast. Suchindan *et al.*, (1987) inferred 97 m^3 beach erosion between Mahe and Talapadi (northern Kerala), containing beach ridges running parallel to its shoreline. Nair *et al.* (2018) assessed shoreline changes from 1968 to 2014 from Poovar to Kasargod (north Kerala) which revealed 29% of coastline is depositing and 60% is eroding. Kumar *et al.* (2014) inferred about 11 km^2 of the island area prograded and 3 km^2 eroded within Cochin estuary.

Beach nourishment is a complex process and causes disruptions that are evened out through cross-shore and longshore transport (Elko *et al.*, 2005). The disruption is pronounced in intertidal zone where beach scarps or vertical cuts are formed (Dean and Dalrymple, 2004; Jackson *et al.*, 2010). Hinkel *et al.*, (2013) analyzed global sea level fluctuations and beach erosion to estimate beach nourishment costs. According to their calculations, some 6000-17,000 km^2 land will be lost to sea level rise, affecting 1.6 to 5.3 million people, expending 300-1000 billion US$ as mitigation costs. In spite of prohibitive costs, mitigation efforts are carried to preserve beach morphology.

Textural Attributes of the West Coast

Rajamanickam and Gujar (1984) investigated sediment depositional environment at Kalbadevi, Mirya and Ratnagiri bays. The sorting, size, and other parameters of sediments is variable amongst these bays. The bivariant plots signify mixed environments for these bays alternating from beach, river, barrier island, and lagoon type. They attributed abnormal kurtosis to palimpsest present at these bays and the presence of ilmenite and magnetite to variable depositional environment or mixed provenance sediment input, even though similar hydraulic conditions prevail. The Sediment texture and geochemistry of Vengurla beach was studied by Hanamgond *et al.* (2017). Gawali *et al.* (2021) used PCA to understand the continentality of beach sediments. Veerayya (1993) analyzed dune and beach samples from Calangute, Colva, and Baina of Goa to find high carbonate content in the foreshore, and low in dune, backshore, and 10 m isobath nearshore samples. Nayak (1999) summarized work carried on Polem (Goa) and Honnavar (Karnataka), based on beach type and geomorphology.

Chavadi and Nayak (1987) attributed stream control on grain size parameters at Shankrubag beach, Karwar. A gradual decrease in mean size from north to south at Karwar beach that signified sediment movement was south and southwest of Kali River (Mislankar and Iyer, 1996; Mislankar and Antao, 1992). They also found Sadashivagad and Karwar beaches comprised different sets of textural parameters despite experiencing similar oceanographic environment. Hanamgond and Nayak (2011) revealed particle size controls the concentration of heavy metals at Arge (south of Karwar) headland beach with different minerals at upper foreshore and lower foreshore. Jayappa and Subrahmanya (1991) revealed grain size distribution and high sand to silt ratio with low heavy minerals within Talapady and Surathkal (south Karnataka) beach sediments. The provenance of these sediments was inferred to be Netravati river basin comprising mostly Precambrian granite gneisses. Dora *et al.* (2011) found high wave action at Kundapura compared to Padukare and Pavinkurve (Karnataka) beaches, which are all eroding under a powerful winnowing process.

Bhat *et al.* (2002) inferred erosion in monsoon and deposition in other seasons with secondary erosion cycles in 1993-1994 at Kudle beach (Karnataka), wherein deposition occurred in moderate energy conditions and the sediment movement was northwards. Bhat *et al.* (2003) carried monthly (Feb 1993 to Feb 1994) morphological and grain size studies on Gangavali beach (Gokarn, Karnataka) and found it gained sediments and underwent a secondary erosion cycle from December to February. The textural characteristics were inferred to have changed from north to south under moderate turbulent energy conditions. The movement of sediments was seen to be towards south. Mislankar and Iyer (1996) found amphibole rich sediments at a pocket beach of Tila-Mati (Karwar) in an area having minimum impact of waves and currents. They related concentration of amphiboles to sphericity and abradation in low energy environment.

The Currents and Tidal Regime Along the West Coast

The west coast tides are semidiurnal with large tidal range between north and south coast. At Cochin (south end) the tidal range is ~1 m and at the Gulfs of Khambhat and Kutch (north end), it is about 8 m, the largest tides of vertical range being present at Gulf of Khambhat (Manoj *et al.*, 2009).The longshore current is variable and estimated sediment transport was southward to the tune of $0.53x10^5$ m^3/y at Vengurla (Chandramohan *et al.*, 1993; Kumar *et al.*, 2006) with 0.008 x 10^6 m^3/y and 0.11 x 10^6 m^3/y gross sediment transport rate (Noujas *et al.*, 2018). George *et al.*, (2020) inferred north to south longshore transport from 0.19–0.37 x 10^5 m^3/y. Asharaf *et al.*, (2001) used surface wave statistics and spectra to understand wave activity at Valiathura coast (south Kerala). They found moderate wave activity prevailed in a fair weather period with a 6 to 17.5 sec wave period and 190-200° wave approach. The rough weather period wave direction had a widespread from 190-260°, periods ranged from 6-13.5 sec, and height ranged from 0.6 to 3.2 m. Seelam *et al.* (2014) estimated net transport in winter months was 10.83 x 10^6 m^3/year (southerly transport at Candolim beach), 9.02 x 10^6 m^3/year (southerly transport at Keri beach), and 0.62 x 106 m^3/year, northerly transport at Miramar beach. The net sediment transport in wave dominated west coast is from north to south premonsoon and opposite in the monsoon months with significant onshore to offshore sediment transport (Rajawat *et al.*, 2005).

Tracking Beach Characteristics Through Mineral Magnetism

Previous Mineral Magnetic Research on Beach Placers (National)

Manjunath and Shankar (1994) are probably the first to use mineral magnetism in the West Coast of India. They studied Gurpur and Netravati (south Karnataka) river bed sediments which revealed concentration of magnetic minerals was more in poorly sorted, fine grained sediments of Netravati, and in the leptokurtic variety of Gurpur sediments. Shankar *et al.* (1996) later deciphered opaque and heavy mineral content of beach and offshore placers using magnetic minerals. Gawali *et al.* (2010) were the first to use magnetic minerals for seasonal characterization of beach placers of Sindhudurg. Bandaru *et al.* (2016) combined magnetic mineralogy and geochemistry to relate hydrodynamics with ambient geology of a part of the Konkan coast. The estuarine domain of Gad (Sindhudurg) river was also investigated by Gawali *et al.* (2019). Singh *et al.* (2014) used magnetic and other proxies to understand the variability of climatic conditions in the recent past from three mudflat core sediments (60 cm) along Kolamb, Mandovi and Tadri (Sindhudurg) that were divided into pre- and post-industrial contamination reflected in the type of mineralogy and rate of sedimentation.

New Mineral Magnetic Case Study

Study Area

The Indian western coastline is passive margin extensional tectonic stress (Pandey *et al.,* 2020). The west coast covers the Indian states of Gujarat, Maharashtra, Goa, Karnataka, and Kerala (Fig. 1). The western coast expose Archaeans and Proterozoic, Deccan Traps, Tertiaries, Laterites, and Recent sediments. The geology is transitioning through this area and disparate exposures are seen from north (basalts) to south (predominantly metamorphics). The geomorphology is seen to change from the Sahyadri ranges to the coastal plains. The drainage, accordingly, assumes diverse characteristics from their origin to the place they enter the Arabian Sea.

The area from where samples were collected for detailed mineral magnetic studies lies at the southern end of the Sindhudurg district comprises Vengurla beach (Fig. 1) forming a narrow coastal strip. The major lithounits exposed in the area belong to the Peninsular Gneissic complex comprising the Sargur Group, Bababudan Group, Kaladgi Super Group, Deccan Traps, laterites, and alluvium.

The methodology of sample collection and magnetic measurements can be found in Gawali *et al.* (2019) (Beach samples were collected seasonally and annually in 2003 and 2004, along 7 and 6 arrays respectively at Vengurla (1-7 arrays). The samples were collected along and across the beaches at regular intervals. However, the width of the beach varies seasonally which makes it difficult to precisely maintain the same sampling points during successive seasons.

The Vengurla Beach seems to be different from one another in terms of morphology and content, though there are likely to be some similarities and lineages. Hence, it is important to integrate the magnetic susceptibility signals obtained at the beach for a clearer understanding of the extant dynamics. The magnetic susceptibility on bulk as well as separated grain sizes have been carried out and presented yearly (2003 and 2004) and seasonally (premonsoon, monsoon, and postmonsoon).

Vengurla Beach

Concentration-dependent Parameter: Magnetic Susceptibility (2003)

A Seasonal collection of beach surface samples was carried from land (120 m) to sea (0 m). Uniform sampling, along with and across the beach, was precluded by variable width. Figure 2 reveals that the seasonal magnetic susceptibility (MS) values are low for the year 2003 signifying low magnetic mineral concentration present at all the arrays during premonsoon (PRM). They are, however, more near sea and less near land and are seen to decrease at arrays from 1 to 7 (Fig. 2).

A marginal rise in magnetic concentration is seen in monsoon (MON) and is prominent at array 1, wherein magnetic minerals are inferred to decrease towards land from the sea, and also from array 1 to array 7 (Fig. 2). An increase is discerned at some locations in postmonsoon (POM). The magnetic minerals can be deciphered to have increased towards sea. This trend is completely contrary to that observed in MON and PRM (Fig. 2). Thus, it can be seen that; magnetic minerals during MON are more at arrays 1, 2, 3, and 7; at array 4 during POM; and PRM at arrays 5 and 6. Of the three seasons, magnetic mineral concentration is more in MON, followed by PRM and POM at Vengurla Beach.

Concentration-dependent Parameter: Magnetic Susceptibility (2004)

The concentration of magnetic minerals is less at all the arrays during PRM 2004, except array 1 at 0 m sampling location (Fig. 3) and they are comparatively more near sea and decrease landwards (Fig. 3). A marginal rise in magnetic mineral concentration is seen in MON and is highest at array 1 at 0 m (Fig. 3) enhancing the average value at array 1 (Fig. 3).

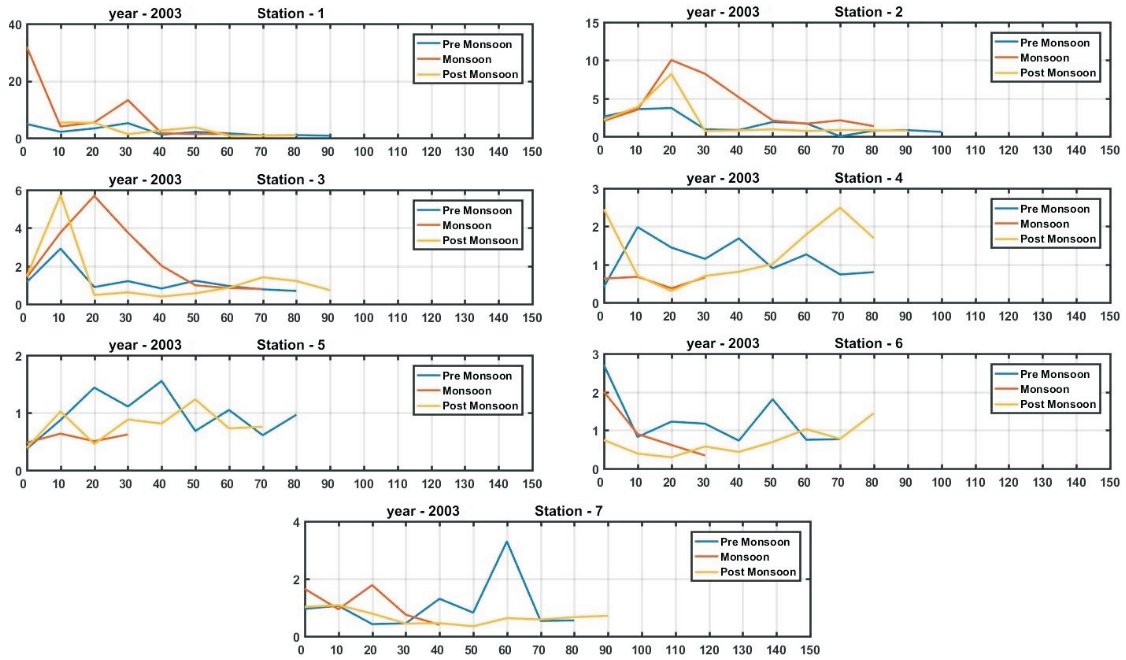

Fig. 2. Magnetic susceptibility variations at Vengurla beach in the year 2003 samples (x-axis is the length in meters interval of the profile and y- axis the magnetic susceptibility).

At the remaining arrays; magnetic minerals are moderately present from arrays 2 to 6, and is low at array 7. The concentration of magnetic minerals decreases from sea towards land. The magnetic minerals are moderately present at arrays 1, 2, 3, 5 and 6 and low at arrays 4 and 7. The average concentration of magnetic minerals at this beach in 2004 is maximum during MON, which is followed by PRM and POM. Thus, on an average concentration of magnetic minerals is found to be more during PRM at array 1; at arrays 2, 4, 5 and 6 during MON; and is more during POM at arrays 3 and 7.

Grain Size v/s Magnetic Susceptibility (2003- Premonsoon)

The magnetic minerals are in different shapes, sizes and domain states or magnetic phases. The grains are segregated for sedimentological and textural studies to understand their inherent properties to assign origin and distance of travel. Magnetic grain size is fundamentally different than physical size, and it signifies the domain state, whether single or multi. Single domain grains are stable magnetically and they retain remanence over longer

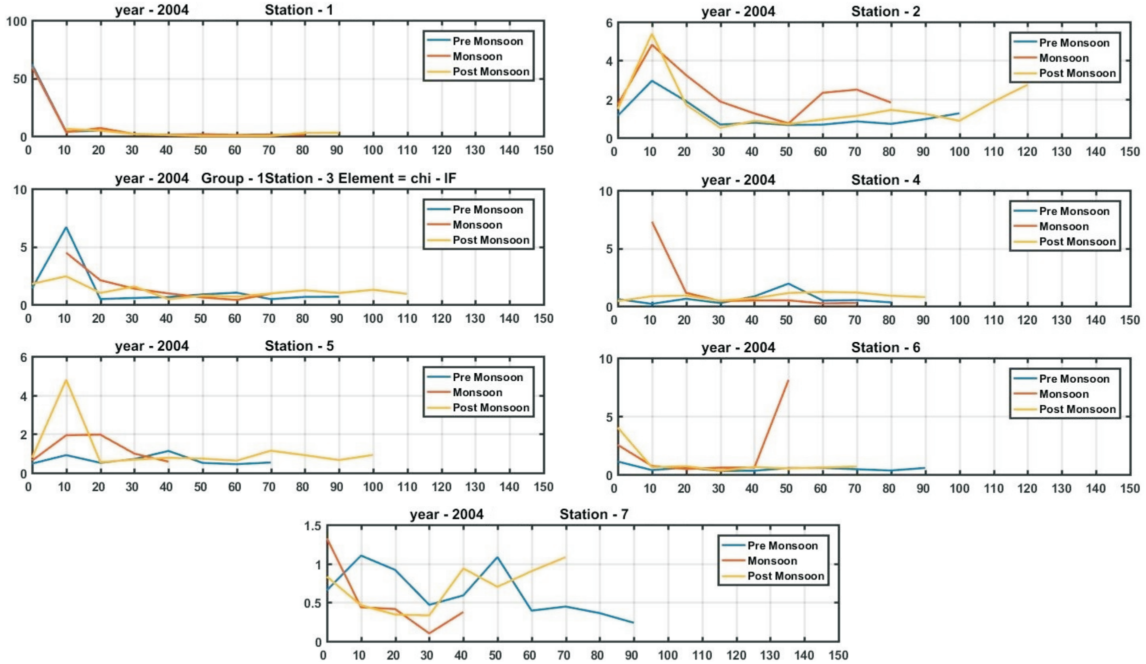

Fig. 3. Magnetic susceptibility variations at Vengurla beach in the year 2004 samples (x-axis is the length in meters interval of the profile and y- axis the magnetic susceptibility).

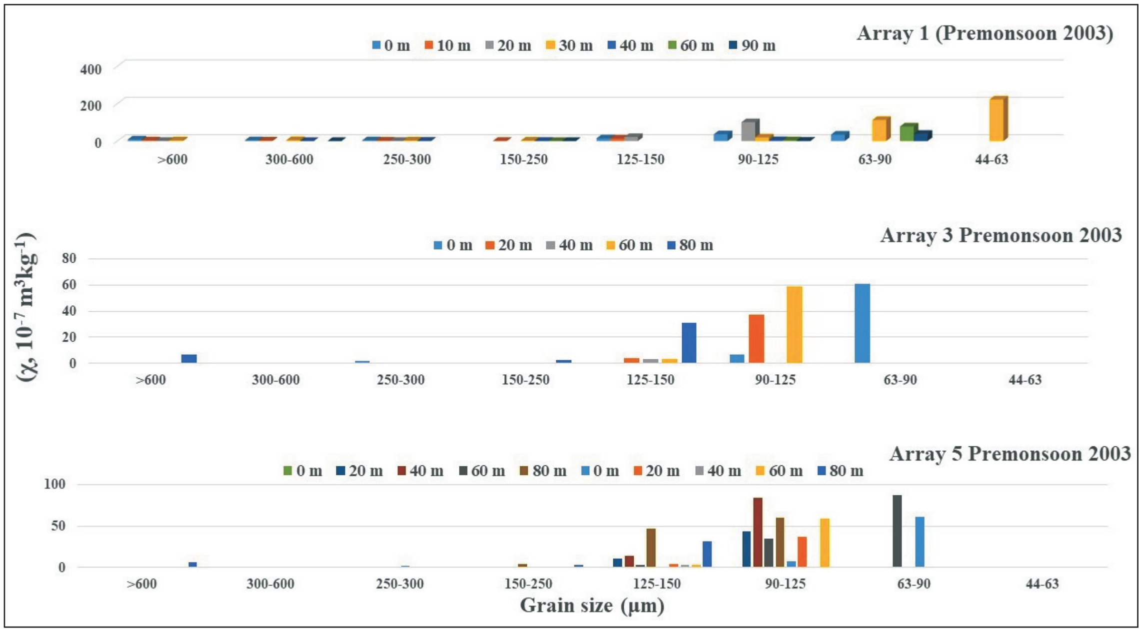

Fig. 4. Magnetic susceptibility variation of sieved beach samples collected at Vengurla in 2003 premonsoon.

geological timescale. However, for cases like present nature, remanence is not a useful property. For studies of present nature, it is presumed that single domain grains overwhelm the multi-domain magnetic susceptibility signatures.

The magnetic susceptibility is governed by the magnetic minerals present in different grain sizes. To understand which grain sizes impart maximum susceptibility, segregated grains in different mesh sizes were used for measurements. Samples collected at 0 m, 10 m, 20 m, 30 m, 40 m, 60 m, 90 m at array 1were used for grain size related MS measurements. The MS at array 1 (0 m, fig. 4), is predominantly controlled by 125 to 63 µm grain size fraction, within which 90-125 µm displays maximum MS and by 63-90 and 125-150 µm size in decreasing order. At 10 m, in comparison to 0 m sampling point, MS is comparatively high within coarse to medium grain fraction (Fig. 4). The 63-90 and 90-125 µm finer grains overwhelmingly impart MS signal at 20 m sample (Fig. 4).

At 30 m sampling point MS is imparted by finest sized grains within 44-63 µm range, followed by 63-90 and 90-125 µm grain sizes (Fig. 4). The 40 m location site at array 1 exhibits low MS compared to earlier sampling points and is more in 90-125 µm grain size followed by 250-300 µm (Fig. 4). The predominant contribution of MS at 60 m location is deciphered to be from 63-90 µm size grains, followed to a lesser degree by 90-125 µm grains (Fig. 4). The 90 m sampling point exhibits low MS, though the finest grain size primarily contributes to the overall signal of MS (Fig. 4).

MS within finest grain sizes from 63-90 and 90-125 µm at array 3, 0 m distance, is seen to be more (Fig. 4) and is high between 90-125 and 125-150 µm at 20 m fine grain sizes (Fig. 4). At 40 m entire MS signal is confined to 90-125 and 150-250 µm (Fig. 4) and at 60 m to 63-90 and 90-125 µm finest grain sizes (Fig. 4), at 80 m distance to the finest to medium grain sizes (Fig. 4).

MS signal at 5th array, 0 m distance, is very low revealing scant presence of magnetic minerals (Fig. 4) and at 20 m it comes from finest grains - 63-90 and 90-125 µm size (Fig. 4). Similarly, finest grains - 63-90 and 90-125 µm grains impart MS (Fig. 4) to sample collected at 40 m distance. Even at 60 m and 80 m, the MS comes from the finest grains - 44-63 and 63-90 µm range (Fig. 4). At 80 m a small contribution from 90-125 µm size grains can also be deciphered (Fig. 4).

Grain Size v/s Magnetic Susceptibility (2004 Premonsoon)

Figure 5 reveals MS at array 1, 10 m distance is imparted by coarse grain sizes from >600 to 90 µm, and a small component comes from 250-150 µm sized grains. At 50 m sampling site, MS is considerably contributed by 125-90 µm grain size, followed by >600, 300-250, 600-300 and 250-150 µm grain sizes (Fig. 5). The 90 m MS is mainly contributed by 300-250 and 150-125 µm grain sizes, but low from >600, 125-90, 250-150 and 600-300 µm grain sizes (Fig. 5).

At the 3rd array, 10 m distance, coarse grains of >600, 600-300, 300-250 µm, and moderate sized grains of 250-150 µm are contributing appreciably to MS (Fig. 5). The sample collected at the same at 50 m distance, an overwhelming MS is contributed by 125-90 µm fine grains, followed by coarse grains of >600 µm and those between 600 and 300 µm size. The contribution of intermediate size grains of 250-150 and 300-250 µm grain size is also substantial (Fig. 5). In the 70 m sample very coarse to coarse grains are seen to contribute to the MS signal (Fig. 5).

At the 5th array 125-90 µm grain size is primarily contributing the MS signal, followed by coarse to very coarse grains (Fig. 5).

Taking into consideration the above results it can be said the MS resides primarily in coarse grains rather than medium or fine ones PRM.

Grain Size v/s Magnetic Susceptibility (2004 Monsoon)

The MS at array 1, 10 m distance is mostly contributed by coarse to intermediate grains (Fig. 6), whereas for 50 m sample MS is imparted mainly by coarse grains and also by intermediate sized grains (Fig. 6).

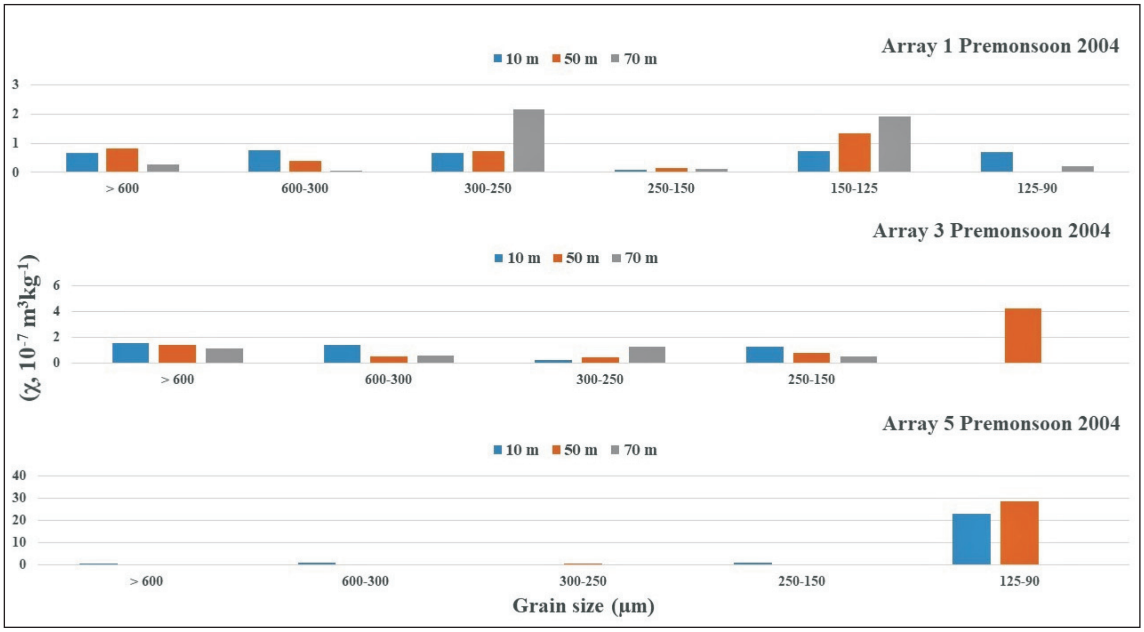

Fig. 5. Magnetic susceptibility variation of sieved beach samples collected at Vengurla in 2004 premonsoon.

In 90 m sample MS resides predominantly in 125-90 μm grains, and substantial contribution comes from still more coarse grains (Fig. 6). At the 3rd array, MS signal of the sample at 10 m is controlled by coarse grains (>300 μm and 125 μm) and a modest contribution from intermediate grain sizes (Fig. 6). The 70 m sample gets majority of the MS from coarse grains, and some from intermediate grains (Fig. 6).

The MS for 5th array samples are controlled by the coarse grains (>600, 600-300, 300-250 μm) with marginal effect from 250-150 μm grains (Fig. 6). The sample from 20 m, gets an appreciable MS from coarse grains (>600, 600-300, 300-250 μm) and some from 250-150 μm grains (Fig. 6). Sizeable MS for 40 m sample is imparted considerably by coarse grains (600-300, 300-250 μm), moderately by very coarse grains (>600 μm) and a little by 250-150 μm grains (Fig. 6).

The sample collected at array 7, 10 m, gets substantial MS from coarse grains (600-300, 300-250 μm) and some from 250-150 and 125-90 μm grains (Fig. 6). 50 m sample gets some MS from coarse grains (>600, 600-300 μm) and appreciably from 1250-90 μm grains (Fig. 6). The array 7, 90 m sample gets substantial MS from coarse grains (300-250 μm), followed by coarse grains of >600 μm size. A Substantial quantum of MS is also contributed by intermediate grain sizes 125-90 and 250-150 μm grains (Fig. 6).

Overall coarse magnetic grains are seen to contribute the MS signal to the MON 2004 samples.

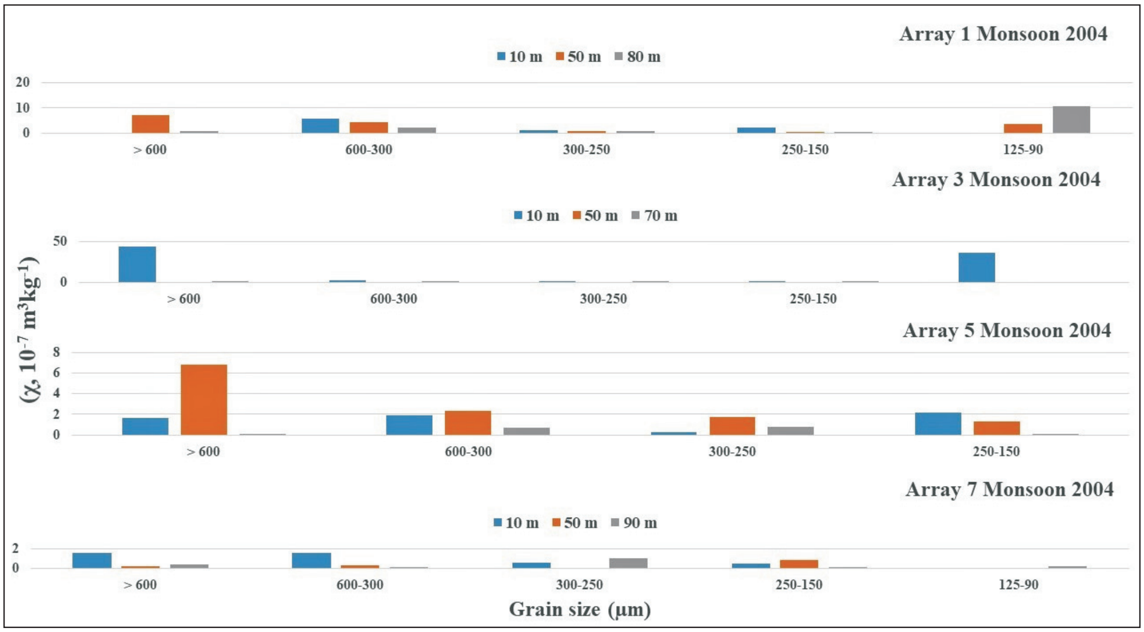

Fig. 6. Magnetic susceptibility variation of sieved beach samples collected in 2004 monsoon at Vengurla.

Grain Size v/s Magnetic Susceptibility (2004 Postmonsoon)

Array 1 MS is predominantly imparted by fine grains (90-63 µm size) to the sediment sample collected at 10 m sampling point (Fig.7) and moderately by coarse and very coarse grains (250 to more than 600 µm size). MS is predominantly imparted by very fine grains (63-44 µm), followed by 90-63 µm, and moderately contributed by fine to coarse grains (ranging from 125 to more than 600 µm) for the sample collected at 40 m (Fig. 7). The MS is predominantly imparted by very fine grains (90-63 µm and 125-90 µm), and moderately contributed by fine to coarse grains to sample collected at 50 m (Fig. 7).

The sample collected at array 3, 10 m distance reveals MS is predominantly imparted by grains in size range 150-125 µm, 90-63 µm, and 125-90 µm, and sparsely by coarse grains (Fig. 7). The MS is predominantly imparted by coarse grains in size range 300-250 µm and 125-90 µm, and moderately contributed by some coarse grains to sample collected at 40 m (Fig. 7). The MS is predominantly imparted by coarse grains in size range 300-250 µm and 90-63 µm, and moderately contributed by some coarse grains to 90 m sample (Fig. 7).

The MS is predominantly imparted by coarse grains in size range 300-250 µm and >600 90-63 µm, and moderately contributed by fine (125-90 µm) and some coarse grains from 0 m sample (Fig. 7). The MS to sample from 60 m is imparted by intermediate coarse grains (150-125 and 125-90 µm) and an appreciable part comes from size ranges between 600-150 µm (Fig. 7).

From the above background of the grain size influence to MS for 2004 PRM Vengurla samples revealed it to be mostly confined to very coarse to coarse grain sizes. The medium and fine sized grains are also inferred to have contributed to MS signal. During MON the percentage of coarse grains imparting susceptibility signal to the bulk MS is more than that of observed PRM. The fine and intermediate grains are seen to impart scarce signal to the bulk MS. During POM too the coarse grains impart more MS in contrast to the fine and intermediate grain sizes.

Magnetic Mineral Identification Through Curie Temperature

Thermal demagnetization was carried out on a few samples and the curves are presented in Fig. 8. Sample collected during PRM from array 2 at 0 m reveals abrupt fall at around 200°C and gradual fall at 620°C indicating two distinct magnetic mineral phases, one having a T_c of ~200°C and the other between 620° and 640°C. The phase transformation at 200°C is an oxidation effect, and the latter indicates the presence of maghaemite (Fig. 8).

The 3rd array 3, at 0 m for the sample collected for POM displays characteristic behavior between 200° C and 400°C (Fig. 8). The drop in SIRM at 250° C and gradual drop thereafter till 400° C and subsequently, it is seen to decrease gradually at about 600° C. The values are affected strongly by the degree of substitution denoting one magnetic phase converting to another. The presence of greigite and/or goethite cannot be discounted, because heating measurements have been done in air. This likely induces the chemical transformation of magnetic minerals. The unblocking temperature of greigite is generally considered to be from 380 to 410°C.The prominent changes between 250° and 400° C could be due to dihydroxylation of goethite to hematite from 200° to 400° C (Przepiera and Przepiera, 2003). The magnetic mineral phase of the samples collected PRM having a T_c of ~ 400° C is seen to change to another phase having a T_c of magnetite, *i.e.*, 580° C (Fig. 8). This could be titanomagnetite converting to magnetite.

The MON and POM sample collected at array 4, 0 m (Fig. 8) displays a gradual decrease and a T_c of 680° C, indicating hematite. PRM and POM array 6, 0 m sample displays T_c of 700° C signifying the presence of hematite (Fig. 8).7th array 10 m POM sample and 30 m PRM sample exhibits identical thermal demagnetization curves whose T_c is between 650°-680° C (Fig. 8) denoting hematite.

The k-T measurements were also carried on select samples and thermal demagnetization curve (Fig. 8) 1st array 50 m sampling site reveals gradual intensity fall (red) post 400°C and abrupt fall at around 620°C indicating the presence of mineral T_c of ~620°C, which could be maghaemite. The cooling curve (blue) follows reverse

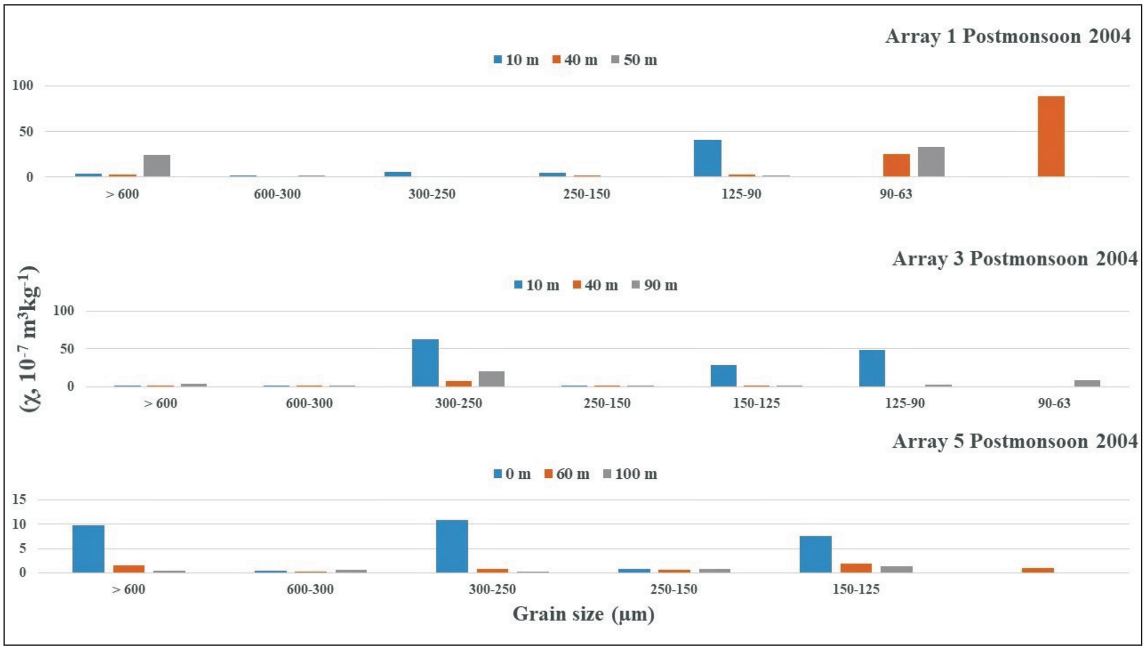

Fig. 7. Magnetic susceptibility variation of sieved beach samples collected in 2004 postmonsoon at Vengurla.

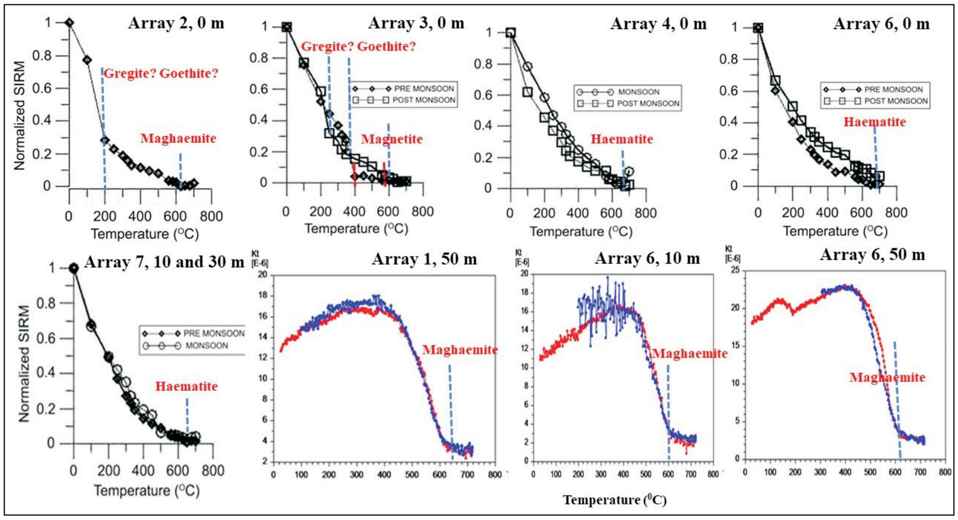

Fig. 8. Curie temperature measurements on samples collected seasonally at different arrays across Vengurla beach in 2003.

pattern of the heating curve. The Thermal demagnetization curve (Fig. 8) for array 6, 10 m, reveals gradual fall (red) in intensity from 450°C onwards and abrupt fall at 620°C indicating maghaemite. The cooling curve (blue) follows heating pattern in reverse but seems to have plateaued between 450° and 200°C, with low amplitude fluctuations. Thermal demagnetization curve (Fig. 8) for array 6, 50 m sample, reveals gradual fall (red) in intensity at about 450°C, abrupt fall at around 620°C, indicating magnetic mineral with a T_c of ~ 620°C, identified to be maghaemite. The cooling curve (blue) follows the same pattern, in reverse, as the heating curve (Fig. 8).

Thus, it can be concluded from SIRM demagnetization that maghaemite is present at array 2, magnetite at array 3, and hematite at arrays 4, 6 and 7. Magnetic susceptibility demagnetization revealed maghaemite is present at arrays 1 and 6.

The magnetic minerals identified at Vengurla are hematite, magnetite, maghaemite, and possibly goethite or greigite. The identification of magnetic grain size and the quantum of magnetic grains present on a beach will make it easy to identify the pockets of beach that undergo deposition and erosion due to wave and energy conditions as well as the longshore currents making it uncomplicated to earmark sediment differentiation. The directionality of sediment accumulation and erosion deciphered from the magnetic studies is also linked to the longshore current flow direction. Grain size analysis is an important tool employed by sedimentologists to classify sedimentary environments and also to delineate transport dynamics. It gives an inkling of shear stress needed by the transporting medium to start and sustain the process of particle movement. Grain size distribution is closely related to shoreline and source distance, parent material, topography, and transport mechanism. It must be noted that the longshore current is variable, and estimated sediment transport at Vengurla was provided by various workers (Chandramohan *et al.*, 1993; Kumar *et al.*, 2006) and net sediment transport rate by Noujas *et al.* (2018).

The magnetic grain sizes and the concentration of magnetic minerals along and across the beaches is a faster way to assess the tracing and sourcing of sediments. The present study has unraveled seaward coarsening of magnetic grains at Vengurla. These samples are those collected at breaker and low water level tract. These are zones of maximum turbulence where high energy dynamics are in play due to wave energy (King, 1972). Hydrodynamic processes are significant in the formation of beach placers (Kurian *et al.*, 2002) and in cross-shore and alongshore transport (Chandrasekar *et al.*, 2005). However, in contrast, Li *et al.* (2002), attribute beach morphology and shoreline geometry to swash zone processes. Different techniques applied for these purposes which were reviewed by Owens *et al.* (2016). Orford *et al.* (2002) cautioned that the cross-beach sediment differentiation and its identification are difficult due to particle shape. Grottoli *et al.* (2019) experimentally deciphered movement of disk- and sphere-shaped sand particles revealing significant longshore current influence signifying swash zone to be the most dynamic part of a beach. Their study revealed spheres traveled longer than disks due to their ability to roll over. In an inhomogeneous beach, clast motion is due to different micro-mechanical factors influenced by shape and size (Buscombe and Masselink, 2006).

Grain size characters are influenced by sediment source, intensity, energy of currents, and mineral composition (Chavadi and Hegde, 1989). A Progressive decrease in grain size is inferred in the transport direction (Pettijohn, 1975), wherein sediment becomes fine, positively skewed, sorted (McLaren and Bowles, 1985). Rill structures are formed by groundwater percolation (Hanamgond, 1990) removing fine particles leaving behind a residue of rolling coarser, coarser or both types of grains/pebbles with increasing strength of the medium. Hegde *et al.* (2006) opine heavy mineral accumulation takes place by winnowing brought about by waves and to a lesser extent by selective movement of a longshore currents.

Thus, the quantum and variability of placer sands along the Vengurla coastal stretch are a function of shoreline geometry and changing seasonal wave climate (Gawali *et al.*, 2010). Li *et al.*, (2002) unraveled concentration and direction of sediment transport is related to change in wind direction. The longshore current intensity is more at Vengurla Beach. In addition to cyclic wave and wind pattern changes, the morphological characteristics can be attributed to beach physical setting (Gawali *et al.*, 2010).The longshore currents are northerly in non-monsoon seasons and southerly during monsoon. The sediments at Vengurla Beach in general, exhibit northerly sediment movement (Hanamgond *et al.*, 2017). The 2004 PRM Vengurla sediments show both northerly and southerly sediment movement in a low energy environment.

Utility of Magnetic Minerals in Assigning Provenance

The magnetic susceptibility variation and the type of magnetic minerals identified at the Vengurla Beach have an important implication in earmarking the provenance. The overall preponderance of magnetite and enhanced magnetic susceptibility in Vengurla MON samples reveals the mineral has been eroded and concentrated along this beach by the energized drainage of a vigorous monsoon during 2003. The monsoon, however, was quite subdued in 2004 and the scant presence of haematite precluded tying the provenance to metamorphic hinterland which has copious iron ore deposits that contain haematite. The abundance of magnetite itself indicates the provenance is Deccan Traps and the longshore currents have brought magnetite to Vengurla Beach. Thus, magnetic minerals can perform a very important role in accurately assigning provenance in areas of complex geology.

Monsoon rainfall is the dominant medium that brings detrital material to the beach during monsoon. In non-monsoon month's; rainfall is very low or totally absent, hence longshore currents and aeolian forces become the primary agencies of detrital transport. These forces could be active in monsoon months also. But, the seasonal rainfall magnitude could be masking the effect. One of the most significant findings of the present study is the quantum of magnetic minerals on a beach can be qualitatively and quantitatively used in assessing monsoonal precipitation. The variability in concentration of magnetic minerals and rainfall are correlating for the corresponding years. Excavated beach samples, if dated, can accurately help to infer historical monsoonal changes with the help of magnetic minerals.

The Konkan Coast have copious amount of heavy minerals like ilmenite and magnetite. This is in addition to index minerals like zircon, kyanite, staurolite and tourmaline present along the bays signifying percentage to be granitic and metamorphic rocks (Gujar *et al.*, 2000). The concentration of heavy minerals is linked to source, shoreline configuration, and extant wave climate (Chandrasekar *et al.*, 2005). During field visit black sands were found layered in the beach scarp at Vengurla beaches. The Mochemad headland, situated in the vicinity of Vengurla Beach, contains coarse grained pink garnet in schistose rocks. Vengurla nearshore bottom sediments were studied by Sathish *et al.*, (2018) which revealed the sediments comprise antigorite, calcite, kaolinite, periclase, muscovite. They measured the average wind speed at Vengurla and found to be 1.2 m/s and current speed 0.34 m/s. They also encountered a good relationship between wave energy and grain size distribution. The Presence of heavy minerals was identified by Nayak and Chavadi (1989) at beaches close to Kali River whose provenance was inferred to be metamorphic and igneous rocks. Chavadi and Nayak (1990) studied heavy minerals to identify provenance of beach sediments around Karwar which they inferred to be metamorphic and igneous rocks, and the general drift of the sediments was from northwest to southeast.

In the provenance of Honnavar Beach (Karnataka) ilmenite was identified by Hegde *et al.* (2006), and heavy minerals identified comprised of ilmenite, zircon, monazite, hornblende, sphene, epidote, kyanite, garnet, and staurolite. They not only inferred its provenance to be an amalgamation of gneissic, granitic, basic, and high-grade metamorphic rocks but also transportation and sorting. Bhattacharyya *et al.* (1997) found west coast ilmenites have high Mn/Mg ratio than the east coast signifying basic rocks dominate the provenance of west coast and charnockite, khondalite, and migmatite of east coast sediments. Nallusamy *et al.* (2013) studied heavy mineral distribution in the barrier island formed between Kayamkulam and Thothapally and also thoroughly investigated the alteration characteristics of ilmenite present in surficial and core sediments. Some of the Kerala beaches are known for their black placers and Mallik *et al.* (1987) identified heavy mineral assemblage from 28 beach and 32 river bed samples having heavy mineral suites of opaque's, hornblende, tremolite-actinolite, hypersthene, and clinopyroxene with distinct 5 mineral provinces along the beaches from north to south resulting from monsoon induced vigorous wave activity, longshore, onshore, offshore movement leading to staggered sorting. They also proposed three stage depositional model. The Heavy mineral assemblage was identified by Rao et al., (2005) from Navaladi and Surungudi (Teri, Tamil Nadu). It revealed high concentration of garnet and ilmenite. Hanamgond *et al.* (1999) and Hegde *et al.* (2006) studied heavy mineral assemblage along the Karnataka coast to assign provenance to beach sands. The presence of rounded rutile, rounded tourmaline, and rounded zircon suggests provenance to be gneisses, schists, and other metamorphic rocks. Green hornblende, epidote, sphene, zircon, ilmenite, and magnetite in the heavy mineral suite are indicative of granitic, gneissic, and basic sources (Hegde *et al.*, 2006). However, the presence of minerals like garnet, kyanite, and staurolite suggests a high-grade metamorphic source, whereas altered-rounded ilmenite suggests reworked older ilmenite. A comprehensive review on provenance analysis is given by Weltje and Eynatten (2004).

However, an erroneous provenance is always likely to be assigned based on a collection of heavy minerals. This study on magnetic mineral proves the point. It is expected that these beaches contain haematite. The beaches, however are low in haematite content and are dominated by ferrimagnetic assemblage of magnetite and titanomagnetite giving rise to two possibilities. The magnetite presence along these beaches is due to transport from the Deccan traps and relict offshore Holocene sands brought by longshore currents.

Conclusions

The previous studies on the west coast assumed the beach and nearshore geomorphology and sediment environments governed by sea level changes. These studies also emphasized upon the variability amongst different beaches within West coast attributed to differing geomorphological setup. The sand characteristics, mineral assemblages, and their volumetric changes helped to correlate the energy conditions and identify the provenance. The studies classify and identify the beaches into stable, eroding, or depositing. Remote sensing and GIS bring in new regional perspectives on the geomorphological studies and the time elapsed imagery studied by present authors produced information on decadal scale shoreline changes. The detailed textural, sedimentological, mineralogical, and geomorphological studies further unraveled many aspects and features associated with hydrodynamics, particle size diagnostics, longshore and rip currents, aeolian and fluvial forces that influence the continent geometry. The new attempts from Vengurla beach reported here further produce an analogue of quantitative/semiquantitative parameters adding to the understanding of beach dynamic processes. Mineral magnetic studies have characterized annual and seasonal variation along these beaches of Sindhudurg district. The beaches contain variable concentrations of magnetite, haematite, maghaemite, and goethite that are linked to changes in longshore processes apart from monsoonal intensity. The presence of Deccan derived magnetite indicates longshore currents transport in contrast to the metamorphic hinterlands. The concentrations of magnetic minerals are correlated with the degree and intensity of the local monsoon. Using magnetic data, we delineate the differing nature and controls of sedimentation over Vengurla beach due to a combination of processes interacting with the beach geometry and morphology. Overall the present overview depicts an increased rate of erosion in the western coast at a number of places whereas deposition is dominant over many. This competitive condition is arising from the advent of longshore currents towards shoreline vis-à-vis increased monsoonal sediment flux enhancing the beach dynamics which may lead to many disastrous conditions over the shoreline. The present overview and approach, therefore, indicate the essentiality of such studies over independent beaches from the west coast as a predictive and mitigative measure.

Authors' Contributions

Praveen Gawali: Investigation, Conceptualization, Writing Original Draft, Visualization, Sampling. **Pramod Hanamgond:** Sampling, Selection of Sites, Conceptualization, Supervision, Editing and Formal Analysis. **Satish Sangode:** Supervision, Visualization, Editing and Formal Analysis. **Milind Herlekar:** Conceptualization, Supervision, Visualization, Validation. **Lakshmi B.V.:** Conceptualization, Visualization, Sampling. **Deenadayalan K:** Conceptualization, Visualization, Sampling. **Prafull Kamble:** Formal Analysis, Data Curation, Methodology, Software, Reviewing and Editing. **Sainath Aher:** Formal Analysis, Satellite Image Interpretation, GIS Mapping, Preparation of Base Maps.

Conflict of Interest

The authors declare no conflict of interest.

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