CrossMark

ORIGINAL ARTICLE

Understanding heavy mineral dynamics using magnetic fingerprinting technique: a case study of North Maharashtra Coast, India

F. Badesab[1] · S. D. Iyer[1] · A. R. Gujar[1] · D. K. Naik[1] · S. S. Gaonkar[1] ·
R. A. A. Luis[1] · P. Shirodkar[1] · S. Naik[1]

Abstract Environmental magnetic and grain size measurements were carried out on sand samples collected from nine sand pits along a 20-km coastal stretch of Arnala Beach, North Maharashtra, India. This study sets out to identify the potential heavy (magnetite) mineral-rich sites in a dynamic coastal system and decipher their enrichment processes. Combination of rock-magnetic and grain size data of the sand pits mirrors the differential heavy mineral fluxes along the coast. Two distinct and well-separated bands of magnetite enrichments were identified. The upper magnetite band (UMB) is more pronounced and shows uniform magnetite enrichment representing the present-day beach erosional state. A well-separated lower magnetite band (LMB) had highest magnetite concentration at Vaitarna River mouth and depicts a strong decrease in magnetite content and clastic (mean) grain size away from the river mouth. This suggests that the NW–SE-directed coast-parallel sediment transport in the past played a major role in the formation of magnetite-rich layers of LMB. A non-enriched zone (NEZ) between UMB and LMB is magnetically weak and showed large variations in clastic grain sizes and possibly represents a period of sediment accretion. A strong correlation between magnetite concentration and magnetic grain size was found for all the sand pit samples, with highest magnetic susceptibility values being dominated by coarser magnetic grains. This relationship needs to be further exploited as a potential fingerprint to identify the heavy mineral lag deposits in coastal environments. Our study explores the potential of using environmental magnetism and sedimentological methods to identify the potential areas enriched in heavy (magnetic) minerals and explains the mechanism of their formation.

Introduction

Heavy minerals such as magnetite, ilmenite, chromite, zircon, garnet amongst others are widespread in coastal systems and help to unravel information related to sediment provenance, transport pathways and depositional environments. These minerals are often found concentrated as lag deposits in rivers, estuaries, dunes, beaches, nearshore and shelf environments. Such lag deposits are formed as a result of a combined action of significant accumulation of detrital heavy mineral concentrations by physical processes including waves, winds and currents (Komar and Wang 1984). Amongst the heavy minerals, the environmental specificity and analytical sensitivity of the magnetic minerals provide an opportunity to explore and utilize them as potential markers for understanding the coastal zone processes.

In placer forming coastal settings, the environmental magnetic methods have been successfully used to map the spatial distribution of magnetic minerals (Zhang et al. 2010), and to identify and discriminate the provenance of heavy minerals (Cioppa et al. 2010; Gawali et al. 2010). The composition and distribution pattern of magnetic minerals were examined to assess sediment sorting and recognize the sites of accumulation and erosion (Hatfield et al. 2010). Based on magnetic mapping of surficial sediments, Badesab et al. (2012) reported the occurrence of

✉ F. Badesab
firoz@nio.org

[1] CSIR - National Institute of Oceanography, Dona Paula, Goa 403004, India

shore-parallel magnetite-enriched belts in nearshore region and explained their formative mechanisms. Gallaway et al. (2012) used magnetic susceptibility measurements in combination with fluorescent paint tracer to examine the enrichment mechanisms and transport dynamics of magnetic minerals in swash zone.

Onshore placers commonly termed "black sand" placer deposits are known to occur along the central west coast of India (Patel 1936; Krishnan and Roy 1945; Roy 1958; Mukherjee and Saxena 1976; Siddiquie and Rajamanickam 1979; Gujar et al. 2004, 2010a, b; Iyer et al. 2010) and were identified based on geophysical, geochemical, mineralogical and petrological studies. The studies concluded that the Deccan trap basalts are a major source of the black sands and the sediments transported by southwest monsoon were sorted resulting in the accumulation of heavy mineral deposits at several areas (offshore and onshore) along the west coast (Siddiquie and Rajamanickam 1979; Gujar et al. 2009). However, hardly any attempts have been made to investigate the economically low coastal stretch of Arnala Beach located between Vaitarna River (North) and Ulhas River (South) within the central west coast of Maharashtra, India. In this study, we set out to magnetically fingerprint the potential heavy mineral-rich zones in the highly transient and ecologically sensitive open-coast environment of Arnala Beach and investigate the influence of littoral zone processes on the enrichment and transport dynamics of the heavy minerals.

Study area and geology

The study area lies within the Thane District of Maharashtra located along the central west coast of India. The 20-km coastal stretch of Arnala Beach between the Vaitarna and Ulhas River mouths is 100–400 m wide and has a flat, gentle beach morphology. In addition, there are berms, raised beaches, sand ridges, mud flats, creeks, runnels, small sand spits and sand bars (Fig. 1).

The geology is dominated by Deccan trap basalts that were emplaced through fissures eruptions during the Upper Cretaceous ($\sim$60 Ma) (Fig. 2). These basalts are porphyritic to non-porphyritic in texture and their mineralogy comprises of magnetite, ilmenite, labradorite, clinopyroxene, olivine, augite and traces of basaltic glass (Anon 1976). The Vaitarna River in the north and Ulhas River in the south are the two major river systems delivering significant sediment load to the study area. The Vaitarna River is about 150 km long, originates from the Triambak hill in the Nasik district and has a drainage area of about 3637 km^2. The average annual run-off is 2937 million cubic metres and the average sedimentation load from June to December is around 3082.5 tons/day (Anon 1976). The Ulhas River is about 135 km long and originates at Tungarli near Lonavala. It has a total drainage area of about 4637 km^2.

Materials and methods

A total of sixteen sand pits, each of about of $1 \times 1 \times 1$ m, were dug along the study area. The distance between pits was about 1 km (Fig. 1). The sediment layers present in the pits were examined and photographed during the field surveys (Fig. 3). In this study, we analysed nine sand pits that had more than two layers (light and heavy) within the pits. The layers were sub-sampled based on the occurrences of the heavy and light mineral layers using a hand-held plastic shovel, and the sub-samples were packed in polythene bags for further analysis. In the laboratory, the material from each layer was mixed thoroughly and four representative fractions were picked and analysed for magnetic measurements. Hence, the one sample point in Figs. 4 and 5 represents the average value of four samples from each layer.

Environmental magnetic measurements

The sub-samples of sand pits were dried and packed in 1-inch cylindrical sample bottles. The magnetic measurements were carried out at the paleomagnetic laboratory of CSIR-National Institute of Oceanography (NIO) and Indian Institute of Geomagnetism (IIG), Panvel Mumbai. Magnetic susceptibility measurements were performed using a Bartington MS2B dual-frequency susceptibility meter. Susceptibility was measured at two different frequencies $\chi_{lf} = 0.47$ kHz and $\chi_{hf} = 4.7$ kHz. Anhysteric remanent magnetisation (ARM) was imparted using 100 mT AF field superimposed with a fixed DC bias field of 50 μT and measured using a Molspin Minispin spinner magnetometer. Susceptibility of ARM is calculated as mass-normalized ARM divided by the DC bias field. Isothermal remanent magnetisation (IRM) of 1T in forward direction and -300 mT in the backward direction were imparted to the sediment samples using MMP10 pulse magnetizer and measured using Molspin Minispin spinner magnetometer. Mass-normalized IRM acquired with a peak field of 1T is assumed to be the saturation isothermal remanent magnetization (SIRM) (Thompson and Oldfield 1986). The magnetic grains were separated from the bulk sand samples using magnetic extraction technique and were later analysed for temperature-dependent magnetic susceptibility measurements using a Bartington (χ-T) system at the Indian Institute of Geomagnetism (IIG), Panvel, India.

Fig. 1 Location map of the study area and sampling sites of sand pits (*P-9*, *P-10*, *P-2*, *P-11*, *P-4*, *P-14*, *P-5*, *P-6*, *P-7*)
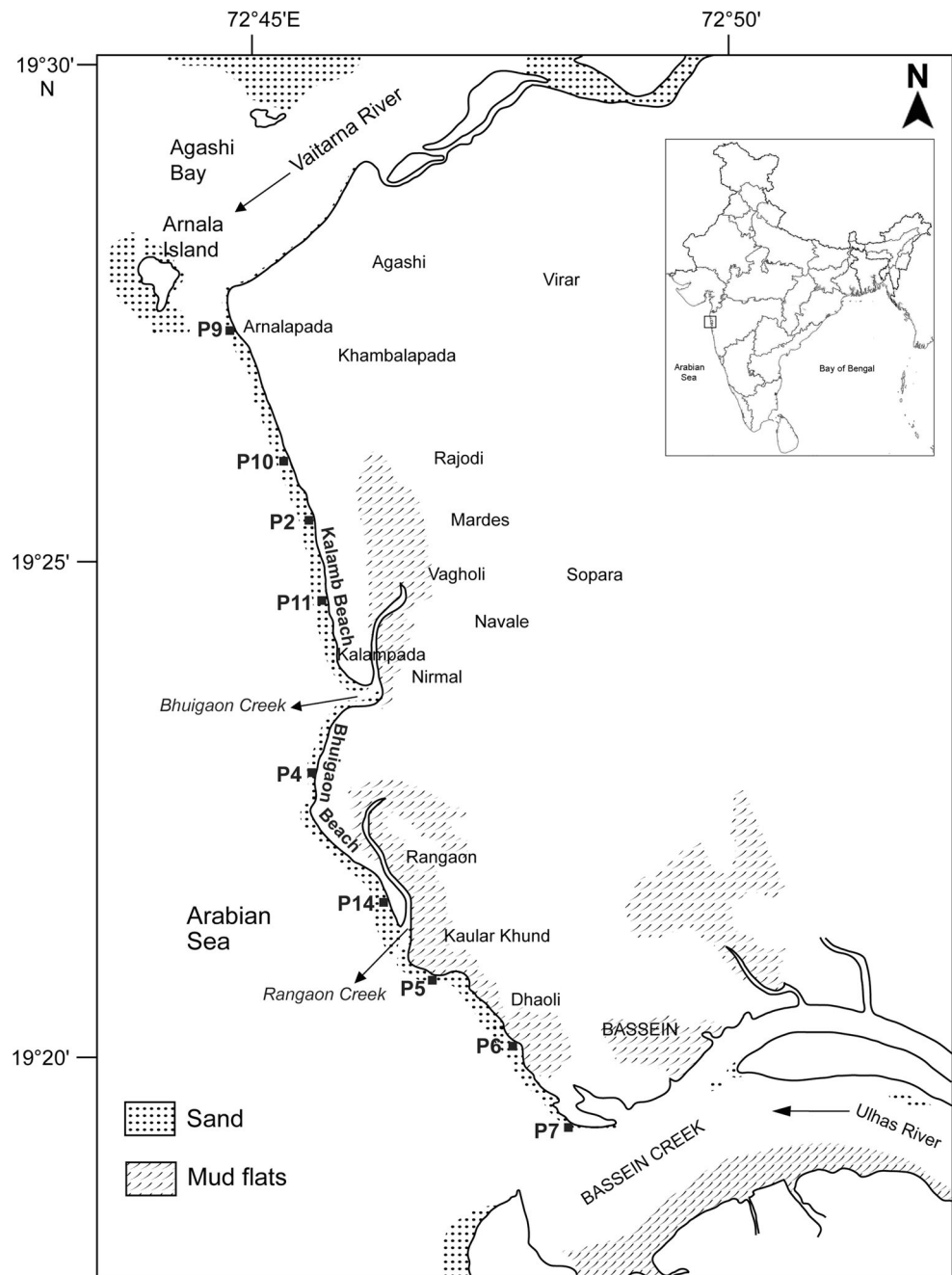
## Grain size determination, heavy mineral separation (magnetic and non-magnetic)

Determination of grains size was made following the method of Folk (1968). The sand samples were washed, dried, coned and quartered. The sub-samples were further treated with 10% HCl to remove carbonate content. Later the samples were dried and sieved at ¼ phi intervals. The grain sizes were calculated from the graphic and moment measures using a computer program (Blott and Pye 2001). The heavy mineral extraction was carried out using bromoform following the procedure of Milner et al. (1962). The separated heavy

minerals were thoroughly washed with methanol to remove bromoform coating from the minerals. These separated heavy minerals were subjected to magnetic separation using a hand-held magnet and SG Frantz isodynamic separator (Model L1) following the methods of Hutchinson (1974).

Electron microscopy and mineralogy

A scanning electron microscope (SEM JEOL JSM-5800 LV) at an accelerating voltage of 15–20 kV was used to capture images of the magnetic and non-magnetic grains in normal and backscattered electron mode. The identification

Fig. 2 Geological map of the study area showing the distribution of main lithologies in the study area (modified from Pandian and Sukhtankar 1989)
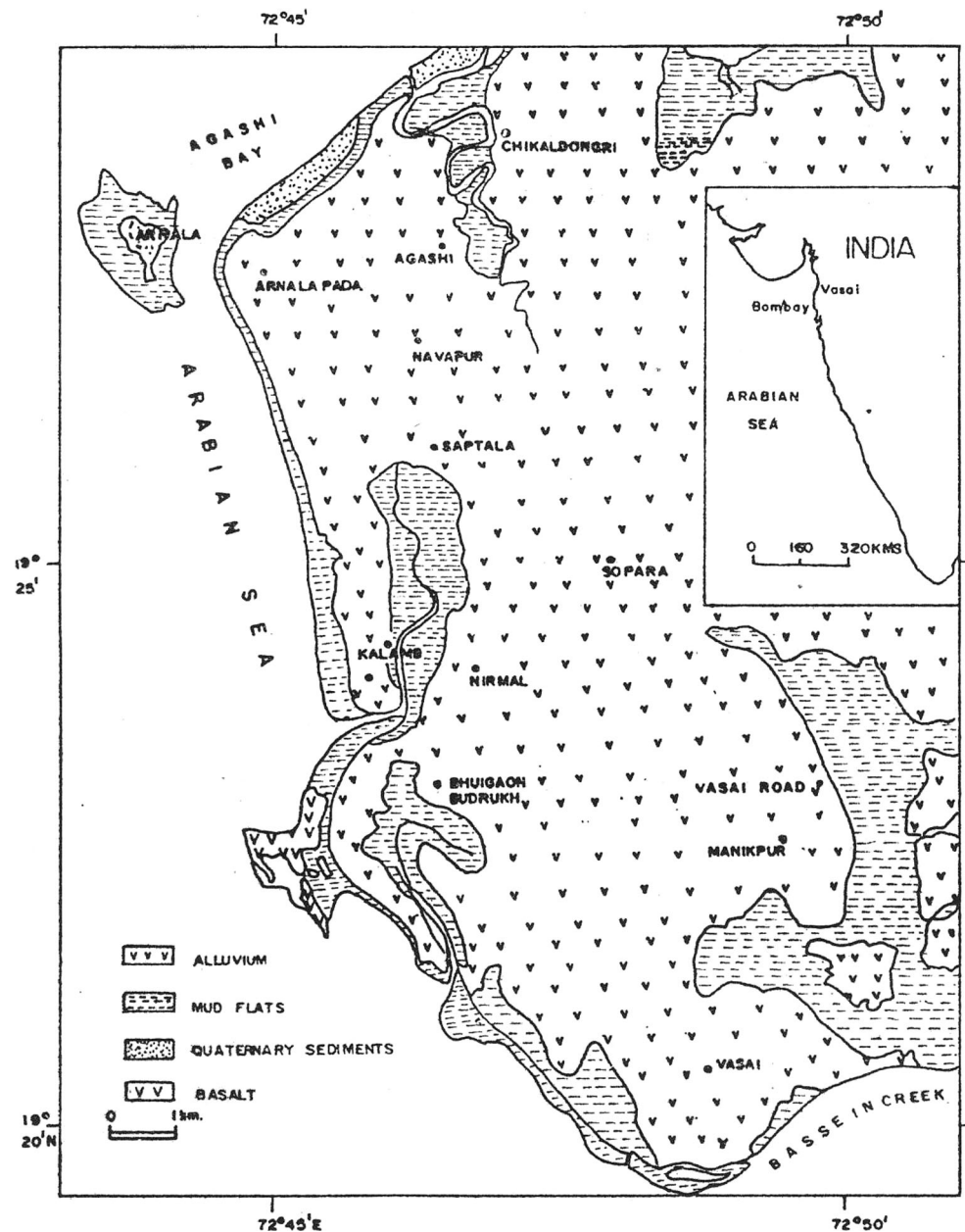

of minerals of selected samples was carried out using a Rigaku X-Ray Diffractometer (Ultima IV). The samples were run from 0° to 60° 2θ at 1 °/min scan speed and Cu Kα radiation ($\chi = 1.5414$ Å).

Results

Down-pit and alongshore distribution of magnetite concentrations

The magnetic susceptibility (χ_{lf}) generally indicates the concentration of magnetic minerals while the inter-parametric ratio (SIRM/χ) mainly reflects the variations in magnetic grain sizes (Thompson and Oldfield 1986). In the study area, magnetic susceptibility data showed alongshore and down-pit variations in magnetic mineral concentration and magnetic grain sizes (Figs. 4, 5b, c). The average values and standard deviation of different magnetic parameters and mean grain size of samples of nine sand pits are listed in Table 1. Based on magnetic susceptibility data of nine sand pit samples, two bands of magnetite enrichments were identified along the study area (Fig. 4). The upper magnetite band (UMB) which extends from Vaitarna River mouth to near the Ulhas River inlet has a relatively low and uniform magnetite concentration. This band occurs within the depth interval of top 0–58 cm. A well-separated lower magnetite band (LMB) showed
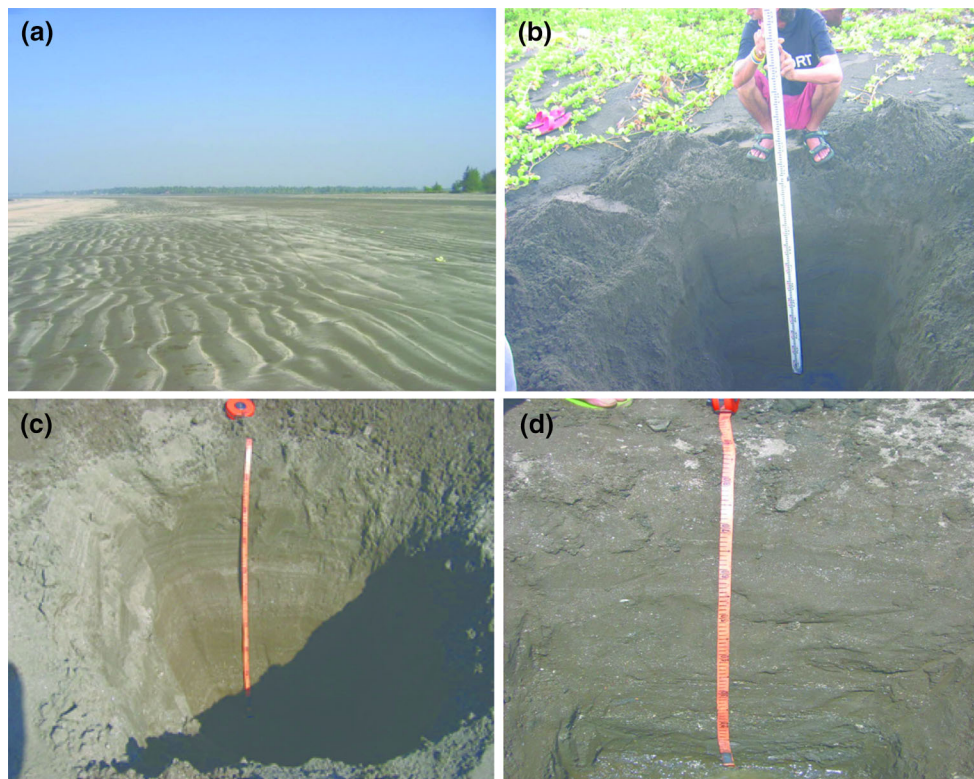
Fig. 3 An example of beach area and field sampling location of sand pits (dimension 1 × 1 × 1 m)
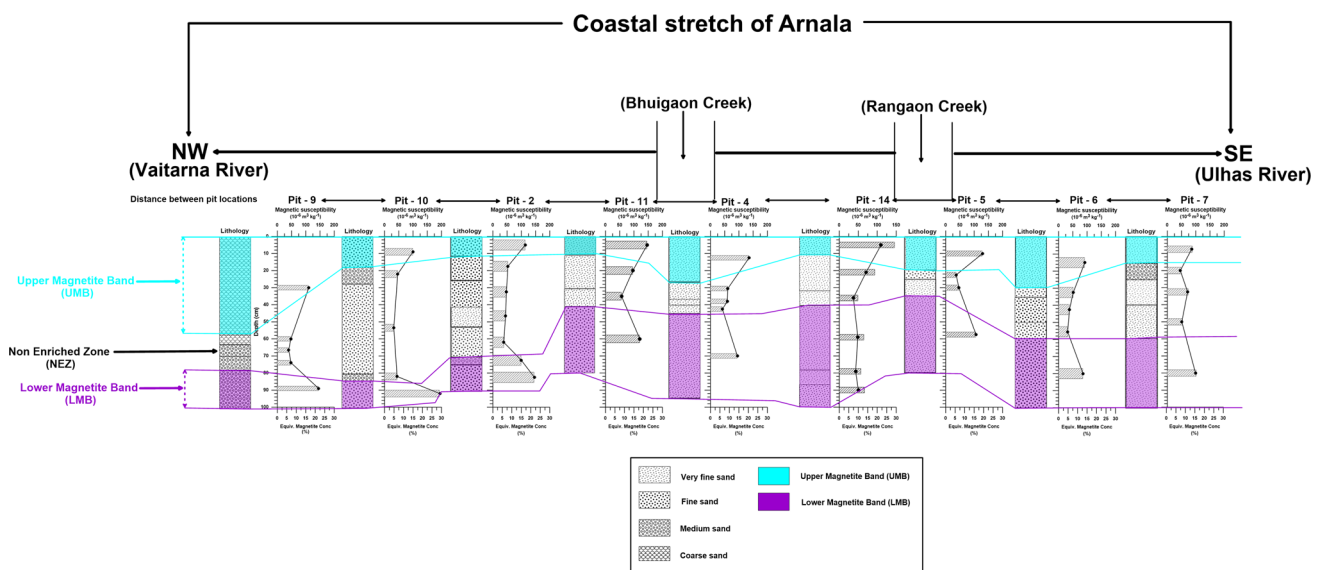

Fig. 4 Lithology and magnetic susceptibility data of the sand pits (*P-9, P-10, P-2, P-11, P-4, P-14, P-5, P-6, P-7*) collected along the Arnala Coast, Northern Maharashtra

highest magnetite enrichment near Vaitarna River mouth (P-9, P-10) and further the concentration decreases with an increase in alongshore distance. The vertical depth of this band varies along the coast (Figs. 4 and 5c). These two bands are separated by a zone of magnetically weak sand interval termed as non-enriched zone (NEZ). A general

trend of down-pit decrease in magnetic susceptibility is observed in all the nine sand pits (Fig. 4). In LMB, the higher magnetite concentrations were found at three sites (P-9, P-10, P-2) which are close to Vaitarna River mouth, while in UMB the highest magnetite content was found at pits P-11, P-4 and P-14 located at the central part of the

Fig. 5 Plots show variations in **a** mean grain size, **b** magnetic grain size indicator (SIRM/k) and **c** magnetic susceptibility in sand pit samples. The upper magnetite band (UMB) is marked by *cyan* and the lower magnetite band (LMB) is marked by *purple colour*, respectively. Each data point marked in *black closed circles* indicates the geo-mean value of magnetic and clastic grain size parameter. Please note that the scale on y-axis has been reversed. The lower SIRM/k indicates coarser and higher values indicating finer magnetic grains
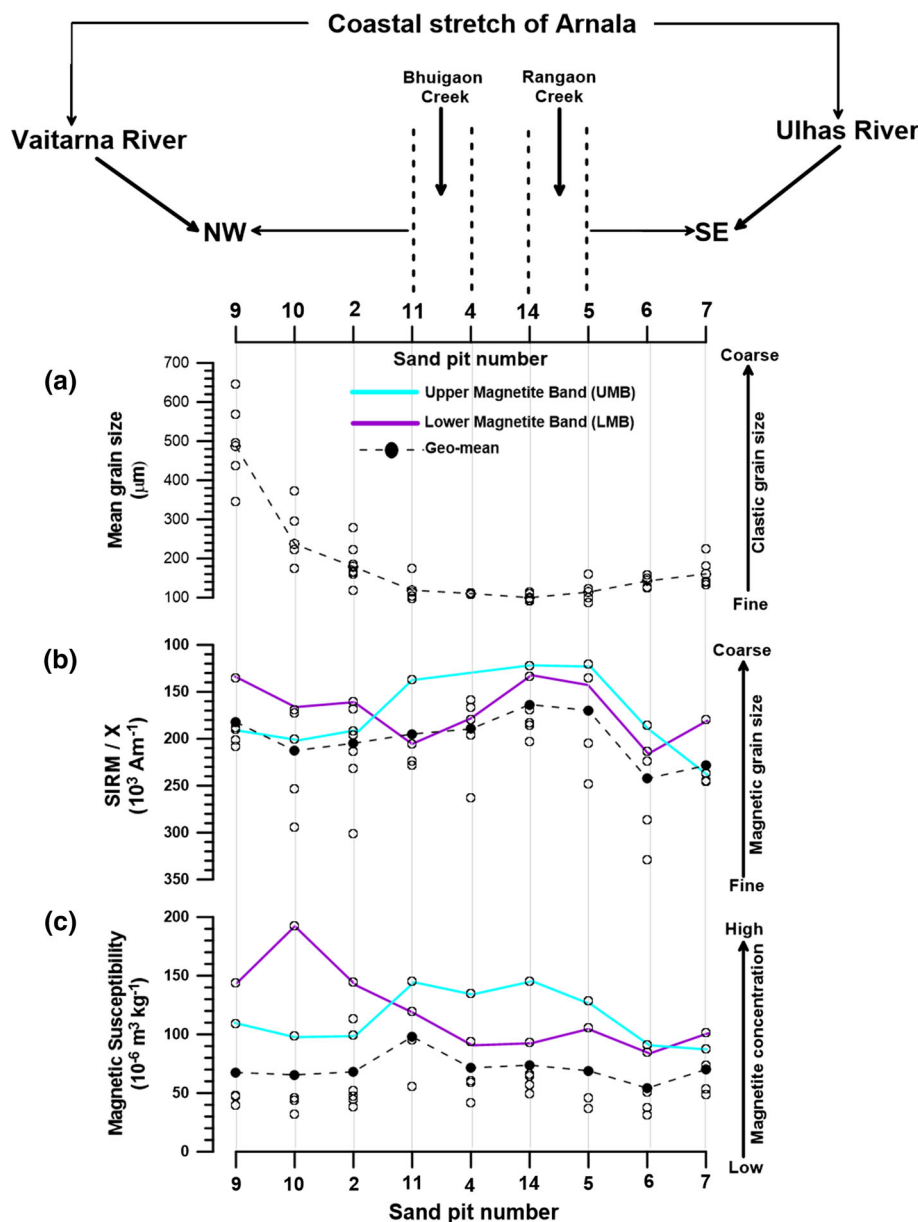
Table 1 Average values and standard deviation of different magnetic parameters and mean grain size of samples of nine sand pits

Magnetic parameters	Average value (mean)	Std. dev
$\chi_{lf} \times 10^{-5}$ m^3 kg^{-1}	78.168	11.166
SIRM $\times 10^{-5}$ m^3 kg^{-1}	14861.47	1096.095
SIRM/$\chi_{lf} \times 10^{-5}$ m^3 kg^{-1}	202.77	13.115
Median grain size (μm)	188.47	10.803

coastal stretch covering Kalamb and Bhuigaon Beaches (Figs. 1, 4, 5c). A general NW–SE trend of coarsening in magnetic grain size is observed in all the sand pits as indicated by a decrease in SIRM/χ ratio (Fig. 5b). The representative curves of temperature-dependent magnetic susceptibility for samples from UMB and LMB are shown in Fig. 6a, b. A sharp decrease in susceptibility at high temperatures (above 550 °C) indicates that the magnetic mineralogy is dominated by titanomagnetite (Fig. 6a–b).

Trends in grain size distribution

The sediment grain sizes in the study area vary from fine to coarse sand (100–650 μm). A trend of down-pit and alongshore fining in clastic grain size is observed (Fig. 5a). The sand pits close to Vaitarna River mouth (P-9, P-10) showed the coarsest sand particles, but the grain size
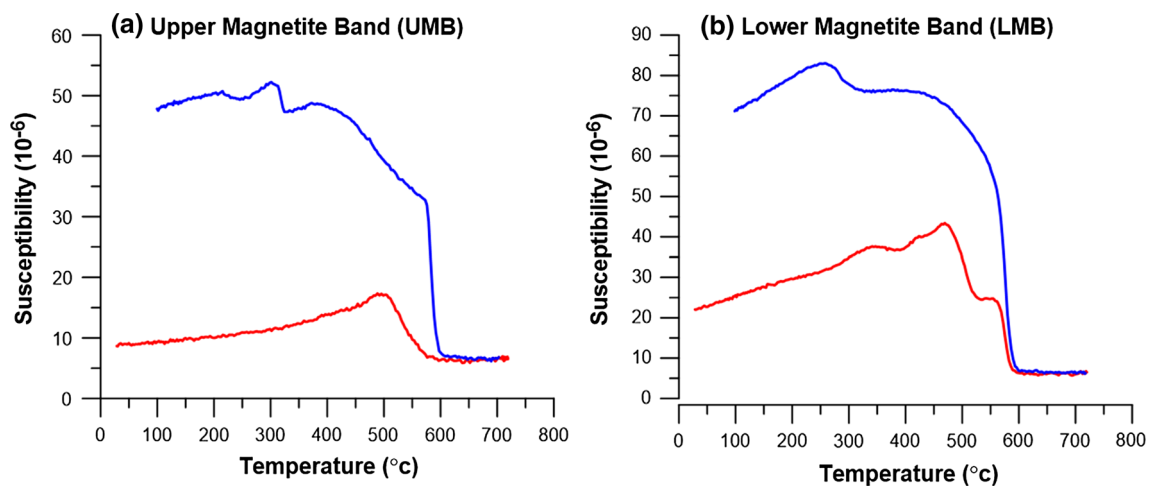
Fig. 6 Plot shows representative temperature-dependent magnetic susceptibility curves on sample from the upper magnetite band (UMB) and lower magnetite band (LMB). The *red* and *blue lines* indicate the heating and cooling curves

decreases gradually (alongshore) towards the southernmost Ulhas River inlet (Fig. 5a). The UMB and LMB are dominated by fine to medium sand (<280 μm), while the sand from NEZ showed a wide range in grain size distributions (100–600 μm) (Figs. 5a, 8c).

Mineralogy

The representative x-ray diffraction curves of magnetic and non-magnetic mineral assemblages from UMB, LMB and NEZ are shown in Fig. 7a, b. Magnetite, titanomagnetite and ilmenite are the dominant minerals in the studied samples. In addition, other minerals including maghemite, rutile/titanite, brookite, hypersthene, ulvospinel, quartz and trace quantities of pyroxenes and zircons were also identified (Fig. 7a, b).

The electron microscopic images of the representative heavy mineral grains (magnetic and non-magnetic) from UMB and LMB sections are shown in Fig. 7c–h. Magnetite, titanomagnetite and ilmenite occur as opaque grains of variable shapes and sizes. The grains appear to be fresh, unaltered and with minimal surface indentation (Fig. 7c–e). Quartz grains have conchoidal fractures, V-shape notches, pits and grooves suggesting that the intense reworking of these grains for prolonged periods must have taken place at the depositional site (Fig. 7f–h).

Relationship between magnetic and clastic grain size

The magnetic parameters χ and SIRM mainly reflect the concentration of ferrimagnetic minerals such as magnetite/titanomagnetite. A positive correlation between χ and SIRM for the sand samples indicates the dominance of ferrimagnetic minerals because paramagnetic and diamagnetic minerals hardly affect the SIRM values (Fig. 8a).

There are differences in χ and SIRM for sand samples from different layers of the sand pits. The NEZ samples possessed the lowest χ and SIRM values compared to UMB and LMB samples (Fig. 8a). A significant relation between magnetic susceptibility and magnetic grain size (SIRM/χ) is observed in all the samples, with highest susceptibility values being dominated by coarser magnetic grains (Fig. 8b).

A correlation between clastic sediment grain size and magnetite content is noticed (Fig. 8c). The higher susceptibility values are associated with the finer clastic grain sizes and vice versa. In general, a relatively weak coupling between magnetic and clastic grain sizes is seen (Fig. 8d). It is interesting to note that this relationship is strong in the samples that possessed clastic grains having <250 μm sizes (Fig. 8d). The UMB and LMB samples showed wide range in magnetic grain sizes, but majority of samples possessed relatively uniform clastic grain sizes, i.e. 70–250 μm (Fig. 8d). The NEZ samples showed large variations in clastic grain sizes but exhibited a narrow range of susceptibilities (Fig. 8c).

Discussion

Beach zone processes and heavy mineral enrichments

Heavy minerals are often found concentrated in rivers, estuaries, beaches, nearshore and shelf environments. They are important indicators of sediment transport, provenance and erosive and accretive states of the coastal regions (Slingerland 1977; Komar and Wang 1984; Frihy and Lotfy 1997; Bryan et al. 2007; Zhang et al. 2010). The formation of placers in beach environments depends on the
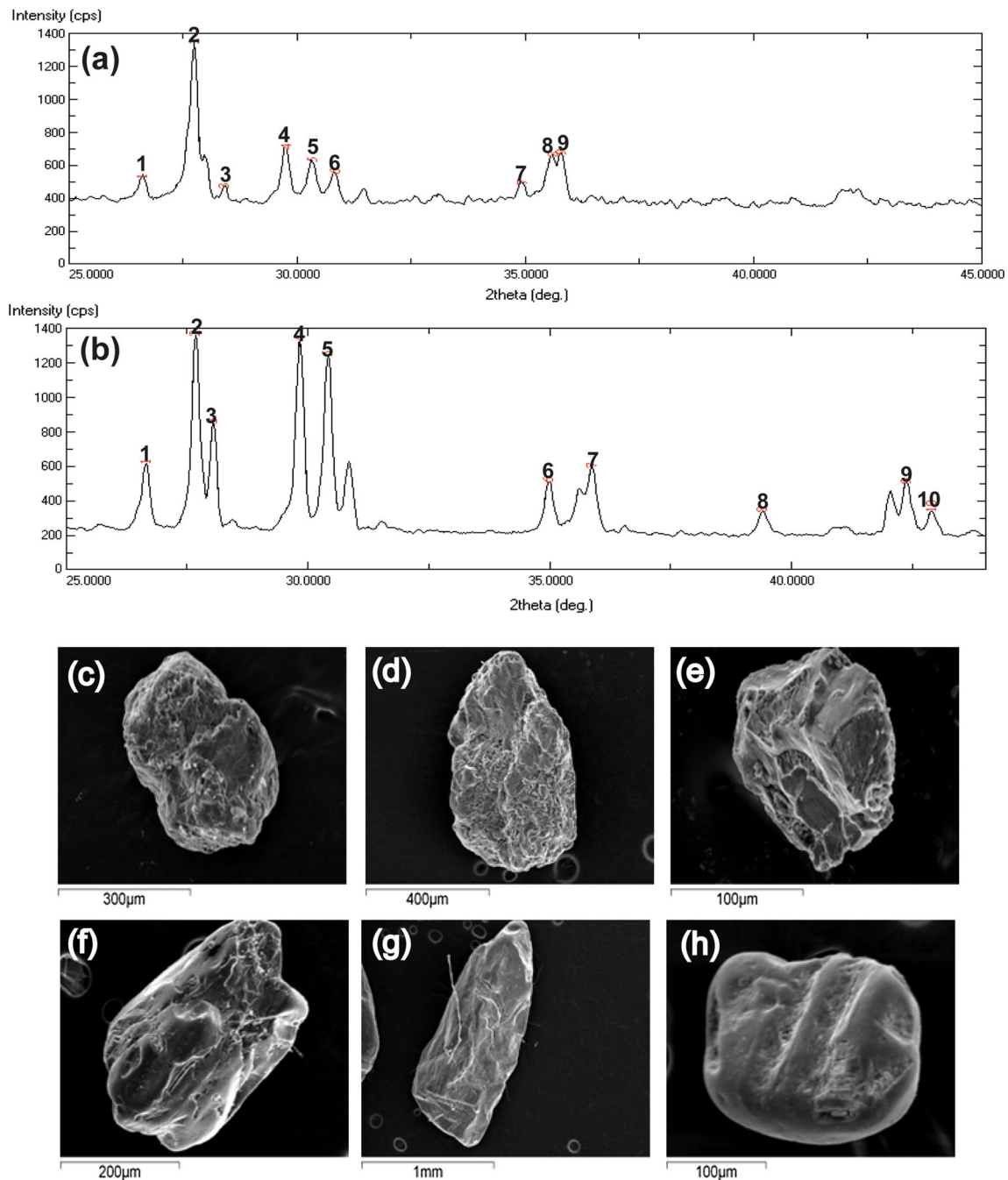
Fig. 7 X-ray diffraction profiles data of representative samples from **a** upper magnetite band (UMB) and **b** lower magnetite band (LMB); and electron micrographs of the magnetic (**c–e**) and non-magnetic sand (**f–h**), respectively. The numbers in XRD plot (*7a*) correspond to (*1*) quartz, (*2*) rutile, (*3*) titanite, (*4*) titanite, (*5*) magnetite, (*6*) titanite, (*7*) brookite, (*8*) magnetite and (*9*) maghemite. In Fig. *7b*, the peaks correspond to (*1*) quartz, (*2*) and (*8*) rutile/titanite, (*3*), (*7*), (*9*) hypersthene and (*4*), (*5*), (*6*) ulvospinel

mechanisms of sediment sorting, selective entrainments, winnowing, swash zone processes, coastal erosions and amount of terrestrial mineral (placer rich) fluxes supplied by the river systems to the coast. The magnetic suscepti-bility data of the sand pits samples from Arnala Coast showed the occurrence of two distinct and well-separated bands (UMB and LMB) of magnetite enrichment. The next task was to decipher the formative mechanism of UMB and LMB.

Past studies based on the mineralogy of placer deposits demonstrated that the highest amount of heavy mineral enrichment occurs in the areas experiencing higher sand erosion (Rao 1957; Frihy et al. 1995; Frihy and Dewidar 2003). They concluded that the episodic erosional events
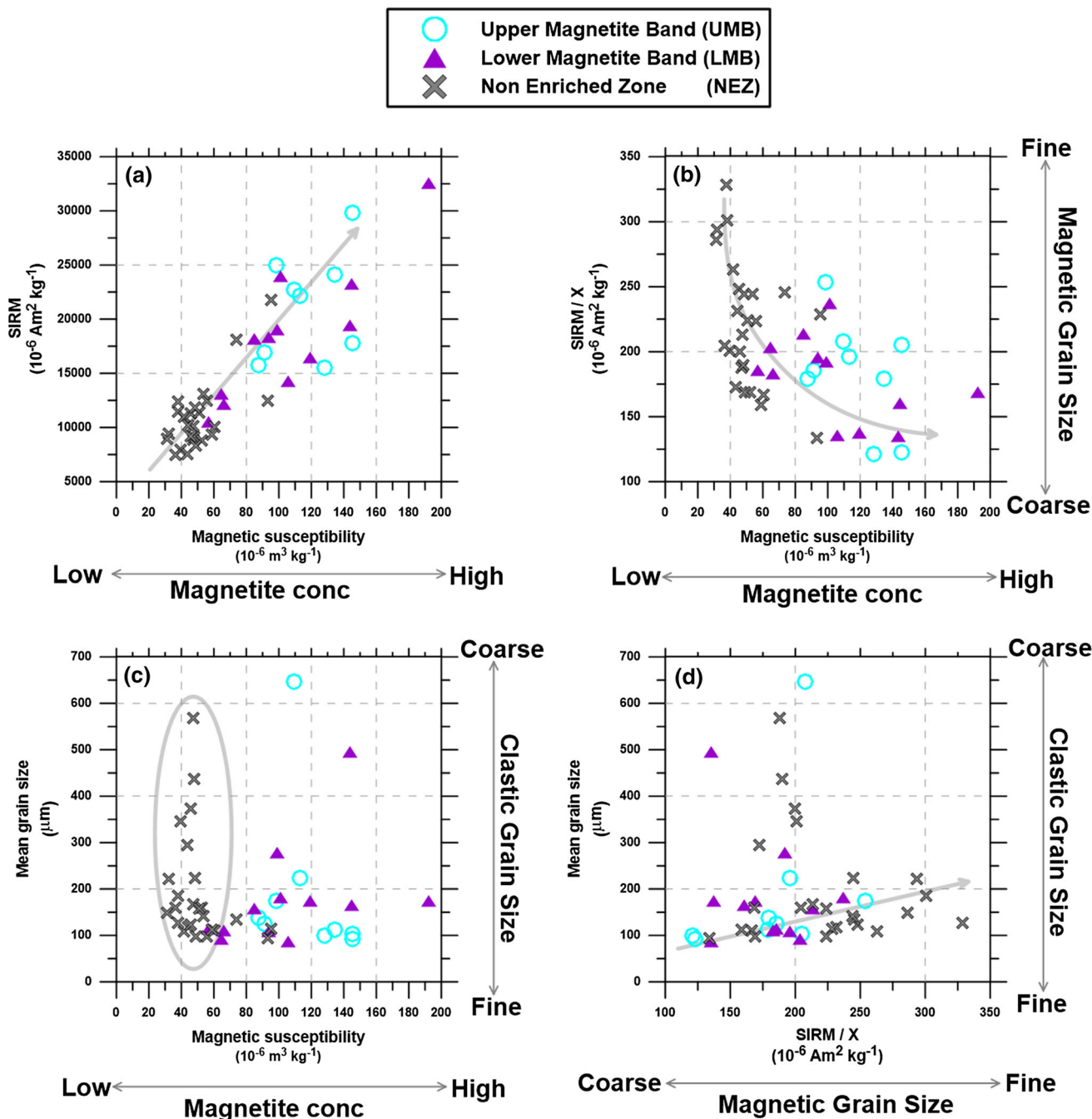
Fig. 8 Scatter plots **a–d** to compare the magnetic parameters and clastic (median) grain sizes of the sub-samples from sand pits

preferentially remove the lighter mineral grains and cause accumulations of heavy mineral grains as placer deposits. Using the preferential erosion hypotheses of Frihy et al. (1995), it was suggested by Hatfield et al. (2010) that higher magnetic susceptibility is associated with areas which are enriched in heavy minerals and experience highest sand erosion in the beach sands of Point Pele National Park, Ontario, Canada. In our study area, we observed that the magnetic susceptibility values in UMB samples are relatively low but possess uniform magnetite

concentration except at sites P-11, P-4, P-14, P-5. Therefore, we propose that UMB is probably formed as a result of intense sand erosional processes occuring along the coast. The higher magnetic susceptibility and dominance of coarse-grained magnetic particles at sites P-11, P-4, P-14 and P-5 could be due to increased amount of heavy (magnetite) rich fluxes supplied by the proximal creeks (Bhuigaon, Rangaon) especially during monsoons when the river run-offs are much higher (Fig. 5b, c). It is highly possible that during fair weather conditions, as the

transport energy decreases these denser magnetic grains gets quickly settled and buried into the sand bed as the result of gravitational sorting forming the enriched zone of UMB. A similar pattern of magnetite enrichment caused by rapid burial of magnetite particles was observed in a swash zone of northern Lake Erie, Canada (Gallaway et al. 2012).

A well-separated lower magnetite band (LMB) showed highest magnetite concentrations only in the vicinity of Vaitarna River mouth (for P-9: $\chi_{lf} = \sim 150 \times 10^{-6}$ $m^3\ kg^{-1}$ and for P-10: $\chi_{lf} = \sim 192 \times 10^{-6}\ m^3\ kg^{-1}$). Therefore, it is highly likely that the higher enrichment at these two sites (P-9, P-10) could be due to the higher accumulation of magnetite-rich load supplied by the proximal Vaitarna River to the coast. Furthermore, these magnetite-rich sands remain accumulated at the sites close to the river mouth forming enriched zones. Once the riverine material reaches the coast, the alongshore sediment transport plays a major role in distribution of sediments along the coast. The sediments are transported further depending upon the energy of the alongshore transport system. In our study area, the strong decrease in magnetite concentration and clastic (mean) grain size away from the Vaitarna River mouth can be directly attributed to the decrease in energy of the alongshore sediment transport system (Fig. 5a,c). Therefore, the majority of the magnetic fraction remain accumulated close to the Vaitarna River mouth forming enriched zones of LMB at sites P-9 and P-10 (Fig. 5c). Therefore, it is highly possible that the alongshore sediment transport played a major role in the formation of magnetite-rich layers of LMB unlike beach erosion which is the dominant process and accounts for the formation of UMB together with inputs from the Bhuigaon and Rangaon creeks. Similar observations were made by Badesab et al. (2012) along Bay of Plenty Coast, North Island, New Zealand. They identified highest concentrations of magnetite at the southern inlet of Tauranga Harbour and the concentration decreases along the coast. They proposed that a decrease in energy of alongshore sediment transport and increasing distance from the source (southern inlet) are the major responsible factors for the observed alongshore reduction in magnetite concentration and fine sand content along the Bay of Plenty Coast, New Zealand. The above explanation provides reasons why magnetite-rich sand supplied by the river and its subsequent alongshore transport are the major factors in the formation of LMB.

Influence of sediment provenance on magnetic susceptibility of beach sands along Arnala Coast

Magnetic minerals are indicative of sediment constituents in coastal systems. The sediment source can significantly affect the magnetic susceptibility of sediments (Oldfield et al. 1985). In the studied area, Vaitarna and Ulhas Rivers are the major drainage systems that flow over the proximal Upper Cretaceous Deccan trap basalts (Anon 1976). In addition, sediments are also contributed from and distributed by the two major creeks, Bhuigaon and Rangaon. In our studied samples, the rock-magnetic mineralogy diagnostic parameters (temperature-dependent magnetic susceptibility) and mineralogical (XRD, SEM) (Figs. 6a, b, 7a–h) data indicated that the beach sands are mostly dominated by relatively higher ferrimagnetic Fe–Ti-rich grains which is mainly sourced from proximal Deccan basalts (Anon 1976) (Figs. 2, 6a, b , 7a–h). This suggests that sediment provenance is not the vital factor affecting the magnetic susceptibility values of beach sands.

Relationship between magnetic susceptibility, magnetic grain size and clastic grain size

We examined the relationship between magnetic susceptibility, magnetic grain size and clastic grain size in beach sands to gain information on the enrichment and transport dynamics of heavy (magnetic) minerals (Fig. 8a–d). In studied samples, the coupling between magnetic susceptibility and clastic grain size is weak (Fig. 8c). The UMB and LMB samples had higher susceptibility in a narrow range of clastic grain sizes (<300 μm), while the NEZ samples showed more uniformity in susceptibility and variable clastic grain sizes (80–600 μm) (Fig. 8c). It is possible that intensive sediment sorting during episodic erosional events might have caused frequent wash out of light and mixed-sized clastic sand fractions of NEZ enabling quick settling and burial of fine and dense magnetic particles on the sand bed leading to formation of enriched zones of UMB. Similar observations were reported in estuarine and nearshore sediments of Tauranga Harbour, New Zealand (Badesab et al. 2012) and Lake Erie, Canada (Gallaway et al. 2012). We propose that the relationship between clastic and magnetic grain size needs to be tested in different sedimentary environments to closely examine the grain size and density-based fractionation and settling of heavy (magnetic) minerals in the coastal environments.

In an earlier study, Badesab et al. (2012) reported a positive correlation between magnetic susceptibility and magnetic grain size in the nearshore sand samples of Tauranga Harbour (New Zealand) and further highlighted it to be a diagnostic of lag deposits. In our studied samples, we observed a similar relationship between magnetic susceptibility and magnetic grain size (Fig. 8b). Our results support the findings of Badesab et al. (2012) and further demonstrate that this relationship could be used as a potential proxy for fingerprinting lag deposits.

Effect of clastic sediment grain size on variations in magnetic susceptibility of beach sand

Studies by Oldfield and Yu (1994), Zhang et al. (2001) and Hatfield (2014) have demonstrated that there is a close link between particle size and variations in magnetic properties. Previous studies have demonstrated that magnetite particles are also found to occur as mineral inclusion in silicate grains and these may have significant influence on the magnetic properties (magnetic susceptibility and magnetic grain size) of the bulk sediments (Hounslow and Maher 1996; Maher et al. 2009). Further, Maher et al. (2009) highlighted the significance of using magnetic mineral inclusions to fingerprint the sediment sources in a tropical fluvial and marine environment of Great Barrier Reef Lagoon, north-eastern, Australia. The magnetic property data of Arnala sands showed that the NEZ samples possessed low susceptibility in a narrow range, but showed a wide range in clastic grain sizes, while UMB and LMB samples showed the reverse trend (Fig. 8c). Now, the question arises as to how the light and coarse-grained (>200 μm) silicate minerals could exhibit such magnetic signals. It is highly possible that the magnetic signal in coarse sand fractions (>200 μm) is probably due to the occurrence of such fine magnetite particles which occur as inclusions (Fig. 8c).

Recently Badesab et al. (2012) suggested that the weak coupling between magnetic grain size and physical grain size is due to the occurrence of fine magnetite inclusions in the coarse clastic grain size fractions in relict pleistocene deposits of Bay of Plenty Coast, New Zealand. Interestingly, the presence of iron-stained quartz in the Arnala beach sediments has already been reported by Ghate et al. (1990). It is possible that the presence of such quartz grains bearing fine iron inclusions may have led to the observed low susceptibility and provides the reasons for the occurrences of wide range of clastic grain sizes in the NEZ samples. The above explanation also provides the reasons for the observed weak correlation between magnetic grain size and clastic grain size in NEZ samples (Fig. 8d).

Influence of coastal morphology on enrichment and distribution of magnetic minerals

The morphology of the coast plays an important role in the distribution and enrichment of heavy magnetic minerals in coastal systems. Different types of barriers including rocky platforms, headlands, tidal inlets and artificially developed jetties, groynes and harbours alter the natural sediment flow and dispersal system resulting in accumulation of sediments on one side and erosion on the other side of the barrier causing imbalance in sediment equilibrium of the coastal systems. Along Bay of Plenty Coast, Badesab et al.

(2012) revealed that the headland at the southern Tauranga Harbour (New Zealand) entrance acted as a major barrier to the normal littoral sediment transport system resulting in accretion of sediments on the upper drift side of the tidal inlet and erosion on the lower side. Similar observations were also made near the Oregon Coast where highest concentrations of heavy minerals were found on the upper side of the headland (Peterson et al. 1986).

In our study area, the open-coast stretch of Arnala Beach is bounded by the basaltic coast-parallel rocky platform which mostly remains submerged during high tide and is exposed during low tide. The Arnala Island, situated at the mouth of Vaitarna River inlet, is another potential natural barrier for the normal sediment exchange between riverine and nearshore region (Fig. 9). We suggest that during fair weather conditions, this coast-parallel rocky platform probably restricts the transport of sand delivered by Vaitarna River, Bhuigaon and Rangaon creeks and also prevents any further cross-shore transport of riverine sand to the offshore regions. Hence, the sand remains accumulated and is forced to moves back and forth (along and cross-shore) between the beach zone and coast-parallel rocky platform (Fig. 9). During monsoon especially when wave energies are higher, i.e. during peak flood, the accumulated sand from the nearshore region is moved into the rivers, creeks and backshore region of the coast. Simultaneously, the sand gets trapped into the backshore region and remains accumulated within the dense mangrove vegetations. During ebb tide, it is highly possible that some of the heavy minerals which had already reached the backshore regions during flooding are not transported back to the nearshore region and in-turn remains deposited in the backshore region forming enriched zones along the coast. The highest enrichment of coarse magnetic grains at sites P-11, P-4, P-14 and P-5 provides support to the above interpretation (Fig. 5b, c).

Conceptual model

We combined our findings into a conceptual model to explain the heavy mineral dynamics on the Arnala Beach of Maharashtra (Fig. 9). The entire stretch of Arnala Beach represents a small littoral cell of the Maharashtra Coast with its distinct sediment supplier (Vaitarna River, Bhuigaon Creek, Rangaon Creek) and open-coast dominated flat gentle beach and nearshore region that acts as a potential sink for the sediments to get deposited. The UMB is formed as a result of intense sand erosional processes and represents the erosive state of beach in present-day conditions. The highest magnetite enrichment found at P-11, P-4, P-14 and P-5 can be attributed to the accumulation of high concentration of magnetite-rich load supplied by the proximal Bhuigaon and Rangaon creek. The LMB has been

Fig. 9 A conceptual model to explain the sorting, transport and enrichment dynamics of heavy minerals along the study area

Littoral Cell of Northern Maharashtra Coast
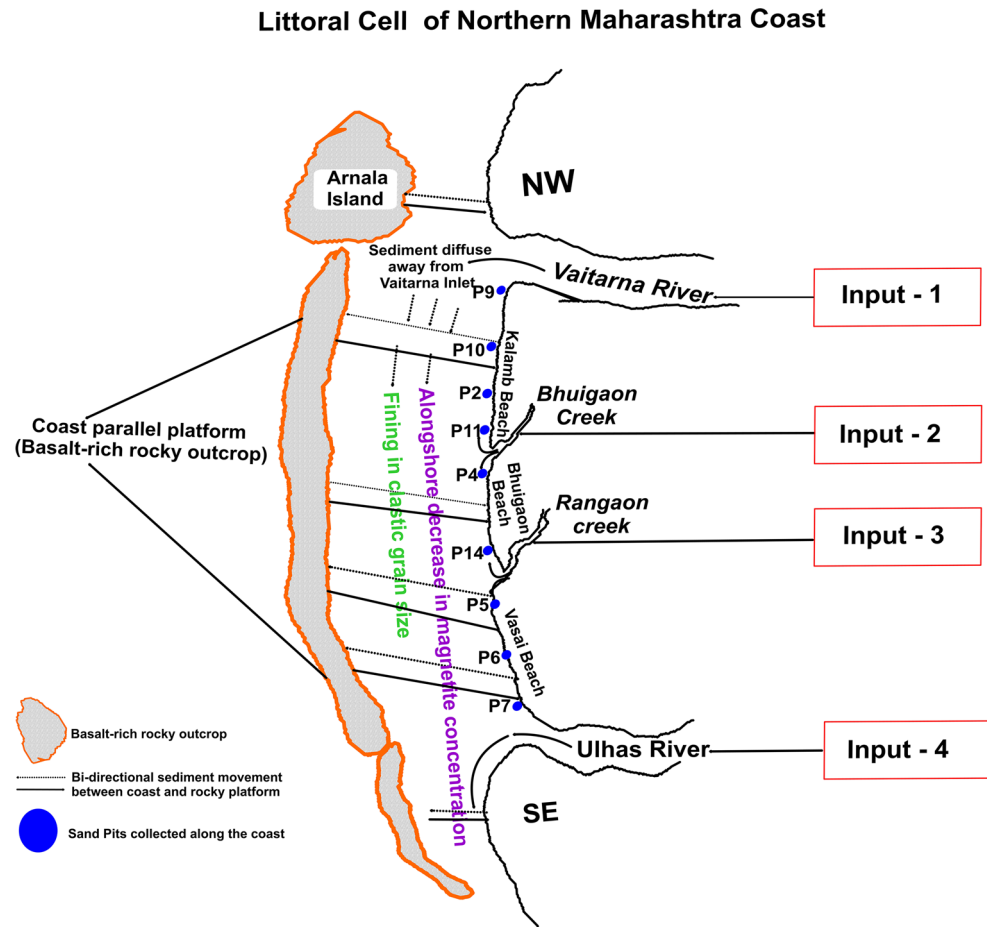
formed where the sediment supplied by the dominant Vaitarna River diffuses away from NW Vaitarna inlet and settles as the transport energy decreases. The NW–SE trend decrease in magnetic susceptibility and mean clastic grain size supports the interpretation. The coast-parallel rocky platform and Arnala Island are the potential barriers which constrain the sediment exchanges and restrict offshore transport of riverine and creek sediments.

Conclusions

Our study explores the potential of using environmental magnetism and sedimentological methods to identify the areas which are enriched in heavy (magnetic) minerals and explains the mechanism of their formation. Our findings are incorporated into a conceptual model which can be applied to understand the enrichment and transport dynamics of heavy minerals in other coastal settings. The upper magnetite band (UMB) is more pronounced and formed, mainly as a result of intense erosional processes occurring along the coast. The lower magnetite band (LMB) is formed as a result of diffusion and alongshore

transport of magnetite-rich sand supplied by the Vaitarna River.

The sands along the Arnala Coast are dominated by high concentrations of Fe–Ti-rich magnetic and non-magnetic minerals, and their distributions are spatially variable along the coast. Higher magnetic susceptibility was found to be associated with the sites which are enriched in heavy (magnetic) minerals as a result of intense sand erosion occurring along the coast. These observations provide clues on the transport and enrichment dynamics of heavy (magnetic) minerals. Our study demonstrates that measurement of bulk magnetic susceptibility of the sand samples allows identification of heavy (magnetic) mineral-rich sites in coastal settings and can also be used as a tool for rapid mapping of placer mineral deposits.

appreciate the immense assistance provided during the seasonal field work by Messrs. Sandesh, Rakesh, Kiran and their able associates. We would thank the editor and the anonymous reviewer for their valuable suggestions which have greatly improved the quality of the manuscript. This is NIO's contribution No. 6015.

References

Anon (1976) Geology of Ratnagiri district, Maharashtra. In: Geological Survey of India, 125th anniversary celebration of publication, pp 1–8

Badesab FK, Dobeneck TV, Bryan KR, Müller H, Briggs RM, Kwoll E (2012) Formation of magnetite-enriched zones in and offshore of a mesotidal estuarine lagoon: an environmental magnetic study of Tauranga Harbour and Bay of Plenty, New Zealand. Geochem Geophys Geosyst. doi:10.1029/2012GC004125

Blott S, Pye K (2001) Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf Process Landf 26:1237–1248

Bryan KR, Robinson A, Briggs RM (2007) Spatial and temporal variability of titanomagnetite placer deposits on predominantly black sand beach. Mar Geol 236:45–59. doi:10.1016/j.margeo.2006.09.023

Cioppa MT, Porter NJ, Trenhaile AS, Igbokwe B, Vickers J (2010) Beach sediment magnetism and sources: Lake Erie, Ontario, Canada. J Great Lake Res 36(4):674–685. doi:10.1016/j.jglr.2010.07.007

Folk RL (1968) Petrography of sedimentary rocks. Hemphill's, Austin, p 170

Frihy OE, Dewidar KM (2003) Patterns of erosion/sedimentation, heavy mineral concentration and grain size to interpret boundaries of littoral sub cells of the Nile delta, Egypt. Mar Geol 199:27–43. doi:10.1016/S0025-3227(03)00145-2

Frihy OE, Lotfy MF (1997) Shoreline changes and beach sand sorting along the northern Sinai coast of Egypt. Geo Mar Lett 17:140–146

Frihy OE, Lofty MF, Komar PD (1995) Spatial variations in heavy mineral sand patterns of sediment sorting along the Nile Delta, Egypt. Sediment Geol 97:33–41

Gallaway E, Trenhaile AS, Cioppa MT, Hatfield RG (2012) Magnetic mineral transport and sorting in swash-zone: Northern Lake Erie, Canada. Sedimentology 59(6):1718–1734. doi:10.1111/j.1365-3091.2012.01323.x

Ghate S, Raghavan H, Rajagopalan G (1990) Petrology and problems of dating karal rocks. J Geol Soc India 36:624–633

Gujar AR, Mislankar PG, Ambre NV (2004) Coastal placers of Konkan Maharashtra: their distribution, mineralogy and geomorphic environment of formation. Indian J Geomorphol 9:123–140

Gujar AR, Angusamy N, Rajamanickam GV (2009) Provenance signature of pre-cambrian and mesozoic rocks in the nearshore placers of Konkan, central west coast of India. Mar Georesour Geotechnol 27(2):115–131

Gujar AR, Ambre NV, Mislankar PG, Iyer SD (2010a) Ilmenite, magnetite and chromite beach placers from South Maharashtra, Central West Coast of India. Res Geol 60:71–86. doi:10.1111/j.1751-3928.2010.00115.x

Gujar AR, Ambre NV, Iyer SD, Loveson VJ, Mislankar PG (2010b) Placer chromite along South Maharashtra, Central West Coast of India. Curr Sci 99:492–499

Gawali PB, Basavaiah N, Hanamgond PT (2010) Mineral magnetic properties of sediments of beaches, Redi-Vengurla coast, central west coast of india: a seasonal characterization and provenance study. J Coast Res 26(3):569–579

Hatfield RG (2014) Particle size-specific magnetic measurements as a tool for enhancing our understanding of the bulk magnetic properties of sediments. Minerals. doi:10.3390/min4040758

Hatfield RG, Cioppa MT, Trenhaile AS (2010) Sediment sorting and beach erosion along a coastal foreland: magnetic measurements in Point Pelee National park, Ontario, Canada. Sediment Geol 231(3–4):63–73. doi:10.1016/j.sedgeo.2010.09.007

Hounslow MW, Maher BA (1996) Quantitative extraction and analysis of carriers of magnetization in sediments. Geophys J Int 124(1):57–74. doi:10.1111/j.1365-246X.1996.tb06352.x

Hutchinson CS (1974) Laboratory handbook of petrographic techniques. Wiley, New York, p 527

Iyer SD, Babu EVSSK, Mislankar PG, Gujar AR, Ambre NV, Loveson VJ (2010) Occurrence and emplacement of chromite ores in Sindhudurg district, Maharashtra, India. Acta Geol Sin 84:515–527

Komar PD, Wang C (1984) Processes of selective grain transport and the formation of placers on beaches. J Geol 92(6):637–655

Krishnan MS, Roy BC (1945) Titanium. Rec Geol Surv India 78:1–32

Maher BA, Watkins SJ, Brunskill G, Alexander J, and Fielding CR (2009) Sediment provenance in a tropical fluvial and marine context by magnetic 'fingerprinting' of transportable sand fractions. Sedimentol 56:841–861

Milner HB, Ward AM, Higham F (1962) Sedimentary petrography. Georde Allen and Unwin, London, p 643

Mukherjee NK, Saxena SK (1976) Mineralogy and genesis of opaque heavy minerals from the coastal placers of Ratnagiri, Maharashtra, India. In: 25th International Geological Congress in Sydney, Australia, pp 217–218

Oldfield F, Yu L (1994) The influence of particle size variations on the magnetic properties of sediments from the north-eastern Irish Sea. Sedimentology 41(6):1093–1108. doi:10.1111/j.1365-3091.1994.tb01443.x

Oldfield F, Maher BA, Donoghue J, Pierce J (1985) Particle-size related, mineral magnetic source sediment linkages in the Rhode River catchment, Maryland, USA. J Geol Soc 142:1035–1046. doi:10.1144/gsjgs.142.6.1035

Pandian RS, Sukhtankar RK (1989) A study of the tidal clastics from Agashi and Bassein creeks, Thane district, Maharashtra. Geol Survey India spl Publ 24:349–354

Patel MS (1936) Magnetite sands at Ratnagiri. In: Indian Science Congress 23

Peterson CD, Komar PD, Scheidegger KF (1986) Distribution, geometry and origin of heavy mineral placer deposits on Oregon beaches. J Sediment Res 56(1):67–77. doi:10.1306/212f8887-2b24-11d7-8648000102c1865d

Rao CB (1957) Beach erosion and concentration of heavy mineral sands. J Sediment Res 27(2):143–147. doi:10.1306/74D70682-2B21-11D7-8648000102C1865D

Roy BC (1958) Ilmenite along Ratnagiri coast, Bombay. Rec Geol Surv India 87:438–452

Siddiquie HN, Rajamanickam GV (1979) Surficial mineral deposits of the continental shelf of India. In: International seminar on offshore mineral resources (Doc. BRGM. 7), pp 233–256

Slingerland RL (1977) The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands. J Sediment Res 47(2):753–770. doi:10.1306/212f7243-2b24-11d7-8648000102c1865d

Thompson R, Oldfield F (1986) Environmental magnetism. Allen and Unwin, London, p 227

Zhang W, Yu L, Hutchinson SM (2001) Diagenesis of magnetic minerals in the intertidal sediments of the Yangtze Estuary, China, and its environmental significance. Sci Total Environ 266(1–3):169–175. doi:10.1016/S0048-9697(00)00735-X

Zhang S, Cioppa MT, Shihong Z (2010) Spatial variation in particle size and magnetite concentration on Cedar Beach: implications for grain sorting processes, Western Lake Erie, Canada. Acta Geol Sin 84(6):1520–1532. doi:10.1111/j.1755-6724.2010.00345.x