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Heavy Mineral Distribution in Shrivardhan Bay, Konkan Coast, Maharashtra

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Abstract: *The coastal bays and inlets act as natural sediment sinks. The heavy mineral analysis of the sediment accumulated in the Shrivardhan bay gives an idea about the transporting agent, the nature of the depositional environment and also the source of sediment. Samples were collected from different morphological units such as the beach, berm, baymouth spit, island inside the bay and also from the mudflats at the bay margins. The heavy mineral assemblage shows low diversity, with the dominance of opaques and pyroxenes in almost all the samples. The second dominant contribution is from zircon and kyanite. The granular heavy minerals, mainly the opaques are concentrated at the highest high tide line along the beach as placer deposits. The samples near the lowest low tide level show more diversity, with the presence of flaky minerals like chlorite, muscovite and biotite in the coarser fractions. The differential distribution of flaky and granular minerals in the bay interior either in coarser or in finer fractions brings out the impact of tidal currents. As far as the provenance is concerned, the percentage of pyroxenes (mainly augite) is high in almost all the samples, as expected from a basaltic province. But the kyanite-sillimanite group, derived from high-rank metamorphics is 'fairly abundant;' to 'abundant' in the western part of the island and the berm area. The only exposure of metamorphics along this coast is further south. This indicates that majority of the material in the sand-sized particles brought into the bay are from offshore sources, rather than the bay catchment. The island samples show relatively high proportions of zircon-tourmaline-rutile, which are mineralogically more matured. This may indicate that the process of sedimentation started earlier at the bay interior.*

Introduction

The coastal zone is looked at, as an open natural system within which there is sediment transport, sediment input and sediment loss (Shuisky and Schwartz, 1983). Sediments bear the signature of the transporting agent, they reflect the characteristics of the depositional environment and they can even give an idea about their possible source of origin. Materials at the point of their destination assume various forms, which are the function of the processes operating and the responses of materials to the processes.

Sources of accumulated sediment in the coast may be (i) the eroded material from the catchment brought in by streams, (ii) material derived from littoral drift and wave action, (iii) wind erosion of dunes and drying shoals, (iv) erosion of the near shore continental shelf, (v) decomposition of organic matter, and (vi) return of dredged spoil (Mc Dowell and O'Connor, 1977). The heavy mineral assemblage may give an idea about the provenance of the sediments and the density and size of heavy minerals reflect on the energy condition of the transporting medium. In coastal bays and estuaries due to the probability of multiple source of the sediment the question of provenance attains special significance. The relative dominance of reworked sediments in the coastal area makes the interpretation even more difficult.

Study area

The Konkan coast exhibits almost a regular sequence of headlands and bays all along the coast. The headlands comprising of basaltic ridges are interspersed by tidal inlets or small bays. Shrivardhan is one such tidal bay. North of Shrivardhan, there are areas which appear to be old bays or tidal basins that have been completely reclaimed. The Shrivardhan bay is partially reclaimed and it seems that the process of siltation is still continuing. Thus the bay provides an opportunity for monitoring the process of siltation. The Shrivardhan bay together with its catchment area lies between 18°0′N to 18°5′N and 73°0′E to 73°7′E. The catchment area of the bay is about 90 km^2, out of which the bay itself covers only about 9 km^2. The bay is backed by basaltic ridges on all the three sides. The 20 m contour line, which closely borders the bay in the northern and southern parts, progressively moves away from the present margin of the bay towards the east, accommodating a relatively large stretch of flat cultivated land lying below 20 m. A number of non-perennial streams, drain into the bay. The streams flowing down from the east are more prominent than the streams flowing down the headlands in the northern and southern parts. The most important stream coming from the east is Galsure (Fig. 1).

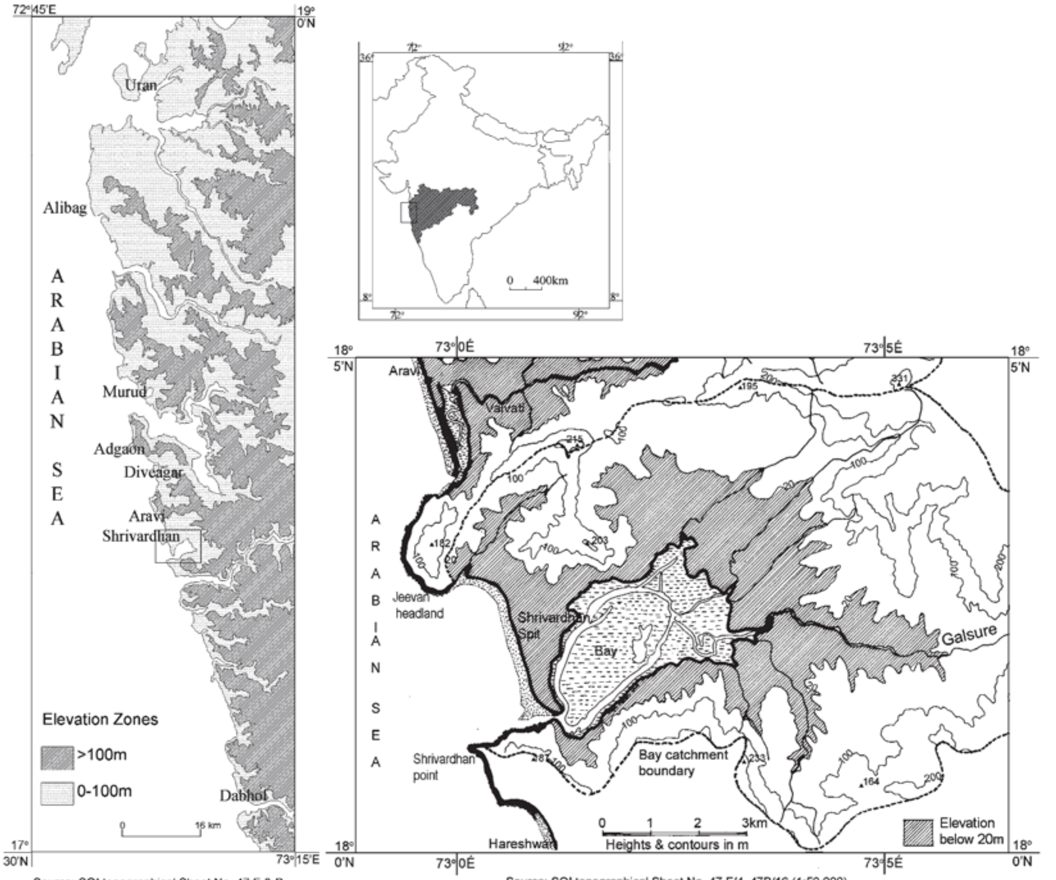
Morphological units

The most significant characteristic of the bay is the development of a very prominent bay mouth spit, which extends from north to south. The Shrivardhan settlement has developed on this spit. The southern most tip of the spit gets fully exposed only during the time of lowest low tide and is yet to get stabilised. The western margin of the spit acts as the present beach, which is backed by a dune line (Fig. 2).

The water inside the bay remains restricted in two narrow arms during low tide, encircling a prominent central island. All along the margin of the bay mudflats have developed, which are usually associated with mangroves.

Geological setting

Being a part of the Deccan lava province, the exposure of Deccan trappe basalt (Upper Cretaceous to Miocene) dominates the geology of the area. The trappe flows south of Kundalika River and north of Shrivardhan are horizontal, but between Mumbai and Panvel and in Alibag it shows a dip of 5°–15° towards the west (Savant, 1980). The flows can be differentiated on the basis of their lithology and also on the basis of the red-bole layer, which may vary in thickness between 1m to



Source: SOI topographical Sheet No. 47 F & B and G (1:250,000)

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Figure 1. Location and details of the study area.

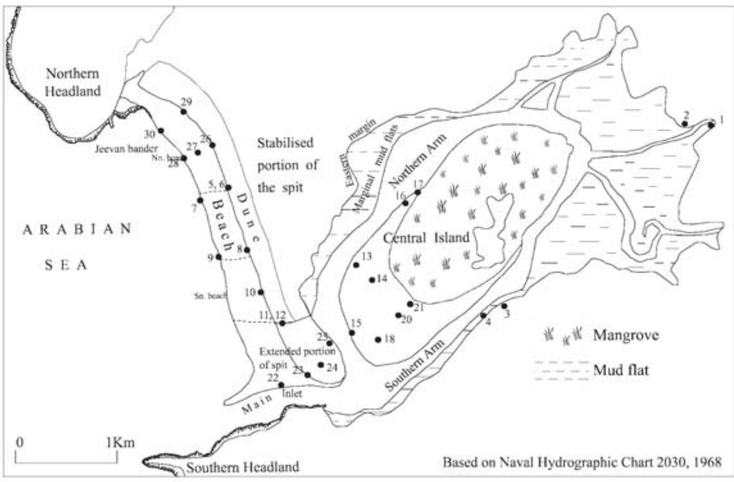

Figure 2. Sample locations in the different morphological units of the study area

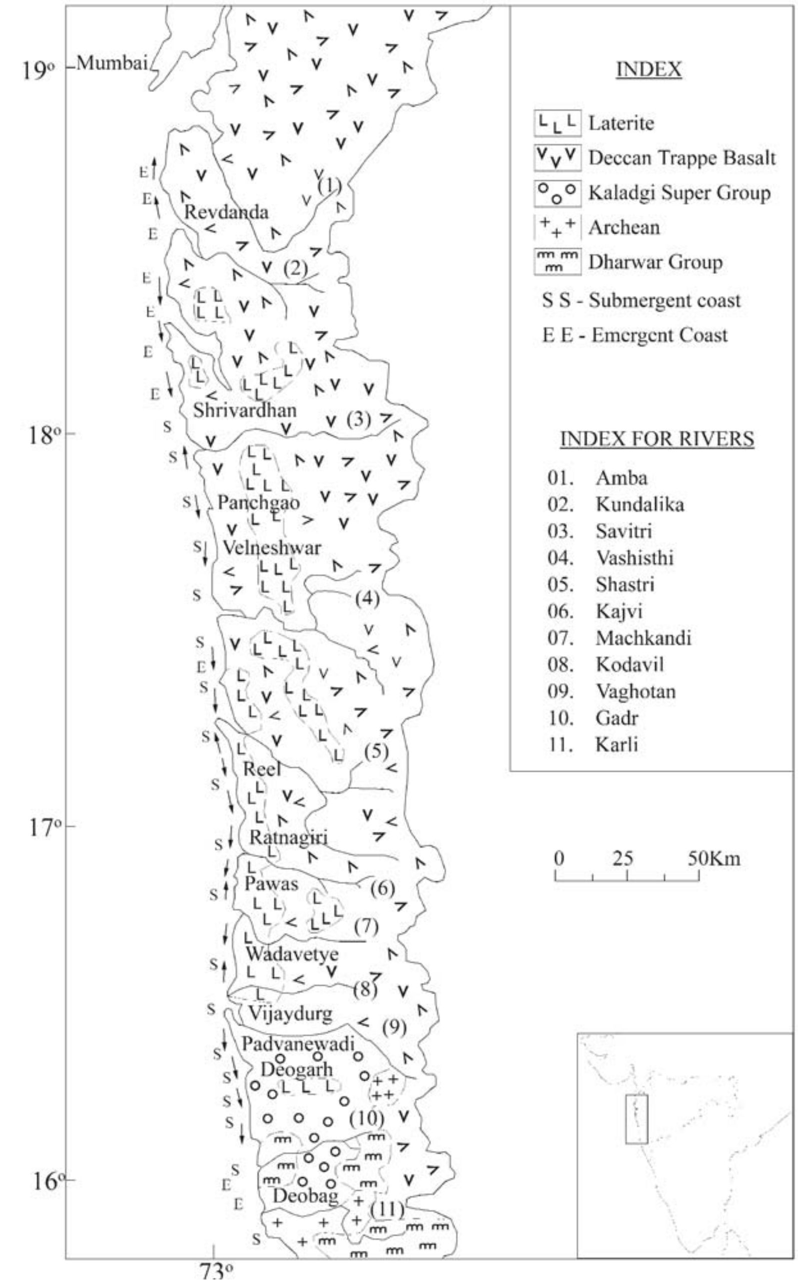

Figure 3. Geological map of the hinterland, major drainage lines and drift direction (Gujar, 1995)

5 m. The area south of Vijaydurg is covered by Precambrian Kaladgis, Archean and Dharwars (Gujar, 1995). Both the Precambrian and Mesozoic formations are overlain by Quaternary laterites (Gujar, 1995). The hill ranges along the coast are capped by

Table 1. Stratigraphic sequence of Konkan and their associated characteristic minerals (Gujar, 1995)

Stratigraphic sequence	Type of rock	Characteristic minerals
Pleistocene to sub-recent	Laterite	Gibbosite, kaolinite, cliachite and ferruginous matter like hematite, goethite.
Upper-Cretaceous to Miocene	Deccan trappe basalt	Labroderite, plagioclase, augite, glass and opaques like ilmenite and magnetite
Precambrian	Kaladgis	Clay, glass, sand, foundary sand, tourmaline, zircon, rutile, staurolite, kyanite, sillimanite, epidote, hornblende, garnet, chlorite, ilmenite, magnetite and pyrite.
	Archean and Dharwars (Phyllites, quartzites, schists intruded by dolerite, gabbro, granite, pegmatite, aplites and quartz veins)	Manganese and iron ore tourmaline, staurolite, garnet, sillimanite, zircon, chromite, quartz and feldspars.

laterites of varying thickness, which occur at different altitudinal levels. Between the indurated (mostly primary) lateritic caps and basalt one finds a loose friable material termed as lithomarge. According to Brűckner, (1987) the Konkan coast, came into existence due to the recession of a fault-line scarp. The basic lava flows are often impregnated by acidic and intermediate intrusive dykes represented by rhyolite, andesite and dolerite (Fig 3). The entire area is crisscrossed by lineaments. The hills and the major rivers like Amba, Kundalika and Savitri follow the trend of the lineaments (Savant, 1980). The stratigraphic sequence, type of rock formation and their characteristic assemblage of heavy minerals in the Konkan are given in Table 1.

Objective

To find out the distributional pattern of the heavy minerals collected from different morphological units of the bay, in terms of their density and size which reflect on the energy condition of the transporting medium.

The second objective is to determine the dominant source of the deposited material i.e. to note whether the material getting deposited in the bay has dominantly offshore source or it is principally derived from the bay-catchment area. This would also give some idea about the dominant processes operating in the area.

Methodology

The collected samples were dried in hot air oven at 60°C to remove moisture. The samples were washed with distilled water by mechanical stirring and decanted carefully. The dried samples were weighed, and the weight loss was noted down weight of sand, silt and clay particles. Before the sediment aggregates were separated into different size groups, they were treated with 30% by volume of H_2O_2 and 1:1 HCl to eliminate the organic matter and carbonate respectively (Ramasamy and Karikalan, 2010). For sieving, mesh sizes ranging from 0.5 φ to 4.0 φ were selected at a regular interval of 0.5φ. This covers a range from coarse sand to very fine sand. For samples finer than 4.0φ, the range up to 12.0 φ was covered with an interval of 0.5 φ. This covers a range from coarse silt to colloid. In the present study only sand-sized particles were considered for heavy mineral analysis which could be studied as grain-mounts. The textural analysis of finer fractions was done by pipetting for determining the silt and clay percentages, but these samples were not considered for mineralogical analysis since infrastructure required for X-ray diffraction was not available.

The collected samples were dry sieved and weighed for the size fractions ranging from 2.00 φ to 4.0 φ. Fractions coarser than 2.00 φ represented insignificant weight percentage in most of the samples. Hence, 0.5 φ, 1.0 φ and 1.5 φ size fractions were not used for heavy mineral separation. For most of the samples one representative from the coarser fragments (2.00 φ) and one from the finer fragments (3.50 φ) were taken into consideration for heavy mineral analysis. In some of the samples the coarser size fraction was so insignificant that only the finer size fractions were separated and analysed. All the size fractions of 2.0 φ, 2.5 φ, 3.0 φ, 3.5 φ and 4.0 φ were taken into consideration for three samples – one from the beach-dune complex (sample 7), one from the southern end of the spit (sample 24) and one from the island (sample 18). The sand particles were suspended in Bromoform for separation of heavy and light minerals (sp. gravity 2.86). The heavy minerals collected were washed with Methyl alcohol and subsequently with distilled water. The washed fractions were dried at 60°C for complete removal of moisture. The required amount of sample was taken by coning and quartering and the heavy mineral fractions were mounted on glass slide with Canada balsam. The grain mounts were studied under binocular optical petrographic microscope using reflected beam and the frequency count of the occurrence of different heavy minerals was carried out with the help of electronic modal counter.

Sample locations

The sediment samples were collected from the different morphological units of the study area viz. the beach-dune complex, extended portion of the spit, the central island and the eastern and southern margin of the bay. Altogether 30 samples were collected for textural analysis from a depth of 8-10 cm from the surface, along 'L' shaped trenches. Among these 20 samples were chosen for heavy mineral analysis. The statistical indices and the distribution of the samples have been given in tabular form (Table 2). Figure 2 shows the locations of the samples collected for heavy mineral analysis only.

The mineralogy of clastic sediments seems to reflect the nature of the source rock, whereas textural parameters are chiefly related to the mode of transportation and the energy conditions of the transporting medium (Friedman, 1961). The inter-relationship of the heavy mineral assemblage and the energy condition of the transporting medium can be interpreted on the basis of the fact that any given flow sorts its bed in a characteristic way, as a function of grain size, density, shape and the hydraulic condition at the time and place of deposition of the constituent particles

Table 2. Granulometric property of the samples from different morphological units (Samples in bold were chosen for heavy mineral analysis)

Sample No.	Morphological Unit	Mean	Median	Skewness	Kurtosis	Sorting
26	Beach HT	3.01	2.9	0.06	1.29	0.52
27	Beach mean HT	2.55	2.65	-0.36	1.82	0.5
28	Beach LT	2.33	2.58	-0.5	1.18	0.75
29	Beach HT	2.99	2.9	0.01	1.19	0.56
30	Beach LT	2.32	2.62	-0.57	1.33	0.79
5	Beach HT	3.13	3.1	0.02	0.38	0.45
6	Beach HT at 40 cm depth	2.94	2.91	0.25	0.25	0.38
7	Beach LT	2.97	2.92	0.23	0.3	0.42
8	Beach HT	2.93	2.89	0.11	0.39	0.47
9	Beach LT	2.82	2.8	-0.23	0.61	0.58
10	Beach HT	3.24	3.28	-0.25	0.32	0.41
11	Berm	3.45	3.5	-0.26	0.07	0.27
12	Berm at 40 cm depth	3.2	3.2	-0.11	0.28	0.38
22	Extended portion of spit	2.53	2.59	-0.29	0.46	0.49
23	Extended portion of spit	2.79	2.79	0	0.24	0.35
24	Extended portion of spit	1.32	1.25	0.33	1.72	1.06
25	Extended portion of spit	2.64	2.68	-0.2	0.53	0.51
13	Island	2.81	2.8	0.03	0.27	0.38
14	Island	3.02	3	0.08	0.31	0.43
15	Island	2.88	2.86	0.14	0.32	0.41
16	Island	4.46	3.68	0.6	17.06	3.29
17	Island	4.9	4.2	0.57	16.63	2.69
18	Island	2.77	2.76	-0.03	0.31	0.45
19	Island	5.03	4.2	0.58	23.52	3.61
20	Island	2.91	2.89	0.1	0.35	0.43
21	Island	3.04	3	0.16	0.34	0.43
1	Eastern bay margin	6.02	6	0.16	35.51	4.4
2	Eastern bay margin	1	6.6	-0.13	30.72	4.36
3	Southern bay margin	2.43	1.4	0.76	27.38	3.81
4	Southern bay margin	2.26	1.7	0.61	18.42	3.12

(Force, 1991; Rittenhouse, 1943; Singerland, 1984). The sorting laws of different types of flow will be governed by the settling, entrainment and transport equivalence of the individual minerals. According to the law of settling equivalence, 'the grains having the same settling velocity accumulate together. Settling velocity in its turn is a function of density, grain size and particle shape (Force, 1991) i.e. the coarser light minerals and the finer heavy minerals will club together. The platy minerals settle slower than spherical particles of the same volume. As far as the entrainment equivalence is concerned, it is more a function of grain size than grain density. Hence, large grains may project out of the bed into the flow and thus be subjected to removal (Force, 1991). Transport equivalence results from the separation of grains on the basis of settling equivalence and entrainment equivalence (Force, 1991). When heavy and lighter minerals of the same average size are supplied to the transport system heavy minerals lag because of their high settling velocities they tend to strike the bed more frequently.

Most sedimentological studies largely depend on textural and mineralogical parameters of sediment to interpret the depositional environment, provenance and the mode of deposition. Majority of these works aim at the heavy mineral distribution in continental shelves, present and ancient bays, beach, tidal flats and lagoonal locations. However, for proper interpretation, mineralogical data are always accompanied by granulometric data. Rivas and Roa (1993) supported the granulometric and heavy mineral data with the investigation of benthic fauna to correlate them with depositional environment. Wilde and Case (1977) tried to determine the local sediment drift condition from the parameter of hydraulic sorting by specific gravity. The work of Ly (1981), aimed at determining the role of coastal erosion and onshore transport in supplying

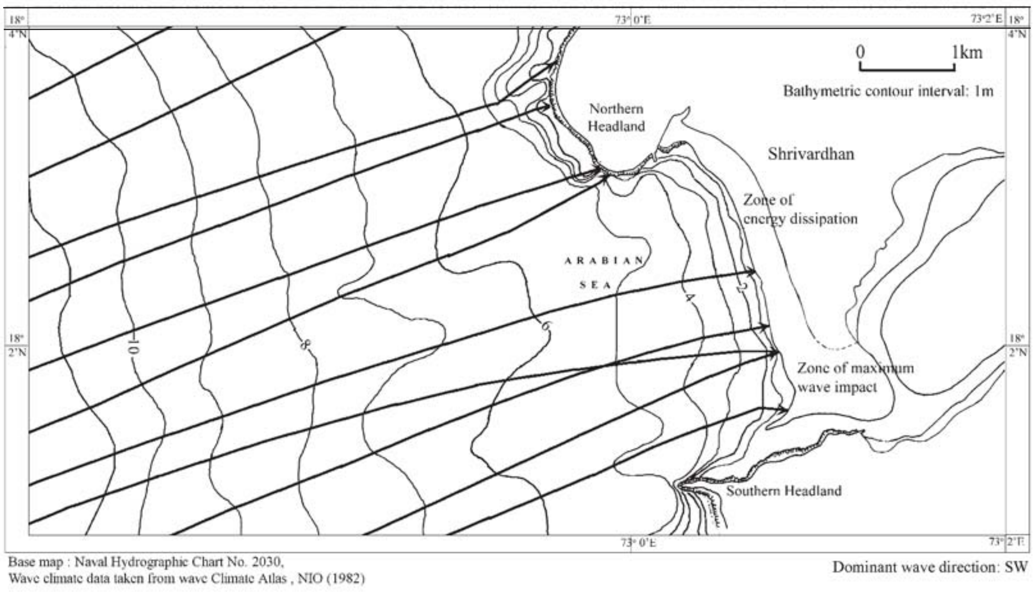

Figure 4. Wave refraction pattern during monsoon showing zones of energy dissipation and concentration

Table 3. Percentage of Opaques in Different Morphological Units

	Beach samples										Berm samples		
Samples	5	6*	7						8	9	10		
size in φ	3.75	3.75	2.25	2.75	3.25	3.75	4.25	Avg.	3.75	3.75	2.25	3.75	Avg.
Opaques	69.47	0	10.85	28.95	14.29	18.31	83.13	30.1	41.38	45.16	69.47	59.78	64.63
	Berm Samples		Extended spit samples										
Samples	11	12*	22			23	24						25
size in φ	3.75	3.75	2.25	3.75	Avg.	3.75	2.25	2.75	3.25	3.75	4.25	Avg.	3.75
Opaques	82.11	69.79	10.47	16.09	13.28	50.62	27.17	6.67	38.04	20.27	35.9	25.61	31.91
	Island samples												
Samples	13	14		15		18						20	
size in φ	3.75	3.75	2.25	3.75	Avg.	2.25	2.75	3.25	3.75	4.25	Avg.	3.75	
Opaques	39.08	64.52	70.51	11.11	40.81	62.96	15.22	70.11	40.22	67.39	51.18	55.95	
	Island Samples			Bay margin samples									
Samples	21			1			4						
size in φ	2.25	3.75	Avg.	2.25	3.75	Avg.	2.25	3.75	Avg.	*Indicates samples collected from 40 cm depth			
Opaques	46.91	47.73	47.32	5.15	17.89	13.52	7.079	53.85	62.32				

sand for the present day beach sedimentation.

Heavy mineral concentration and diversity in selected grain size classes

After the analysis, 18 heavy mineral were identified, with specific gravity ranging from 3 to 5.3, which has been referred to as light-heavy minerals by Mallick (2004). These include augite, diopside, hypersthene, tremolite, hornblende, glaucophane, chlorite, biotite, muscovite, kyanite, sillimanite, garnet, zircon, tourmaline, rutile, epidote and opaques. For the ease of discussion and interpretation augite, diopside and hypersthene have been clubbed together under pyroxenes and tremolite, hornblende and glaucophane grouped together under amphibole. Since kyanite and sillimanite were seen to occur together in majority of the samples, these have been clubbed together as kyanite-sillimanite group.

The beach samples

The samples along the beach were collected from north to south, following the direction of the dominant long shore drift (Kunte and Wagle, 2001). Samples 5, 8, 10 and 11 were collected from the highest high tide line (HHTL) and samples 7 and 9 were collected from the lowest low tide line (LLTL). It may be noted that samples 6 and 12 were collected from a depth of 40 cm from the surface near sample 5 and 11 respectively. Texturally the samples from the HT zone are relatively finer and better sorted than the LT samples.

Majority of the samples in the beach area show considerable proportion of opaque minerals (36% to 83%) comprising of illmenite or magnetite which are mostly granular in shape (sp. gravity 4.7 to 5.26). Opaque minerals derived from the Deccan basalts are not uncommon in this part of the coast and at several locations they form placer deposits. The higher densities and finer grain sizes make the opaques more resistant when carried as part of the bedload or in suspension. The differences in settling velocities

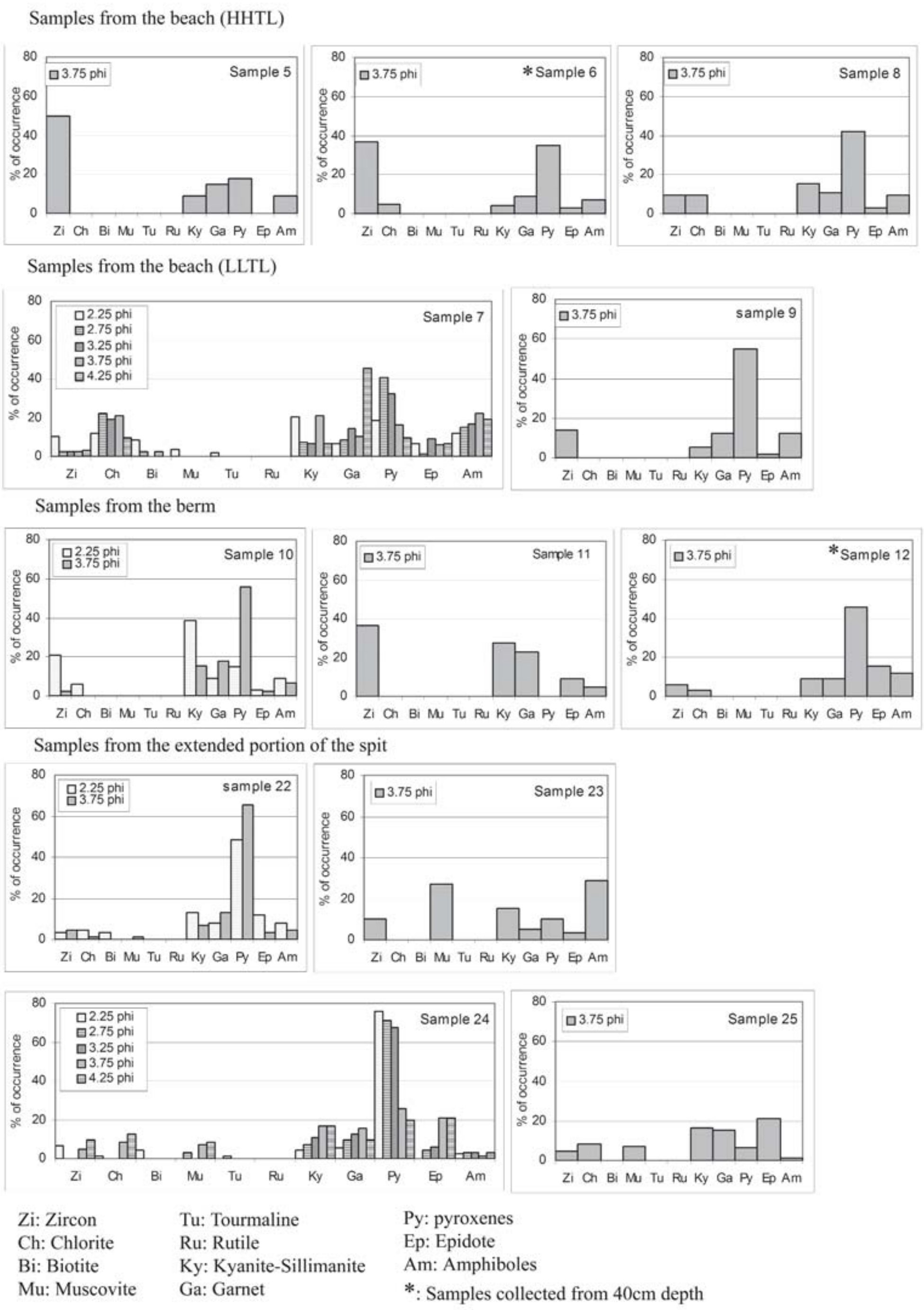

Figure 5a. Heavy mineral assemblage of beach and berm samples

determine the concentration of opaques (Komar, 2007). Sizeable proportion of ilmenite and magnetite has been observed at number of bays and headlands along the Konkan viz Jaigad, Vijaydurg, Ambalgarh and the some of the bays such as Varbada, Rajapur, Kalbadevi, Mirya etc. (Gujar, 2002; Gujar *et al.*, 2007, Rajamanickam, 2001). The Konkan, with an average rainfall of 3000 mm yr-1 experiences chemical weathering which is responsible for liberation of heavy minerals from source rocks (Gujar *et al*., 2010). The opaques are more concentrated near the HHTL and that too in the very fine sand fractions (3.75 φ). The placer minerals are deposited at the HHTL during the spring tide or storm condition, which the subsequent tide fails to remove. However, the middle beach sector, represented by sample 8, shows marked decrease in opaque percentage (41.38%) even near the HHTL (Table 3). This may be explained by the wave refraction pattern in this part of the coast. The approaching wave orthogonals during the monsoon months diverge at the middle beach sector indicating energy dissipation at this location (Fig. 4). A low energy regime at this part may not allow the incoming waves to push-up the opaques up to the HHTL. It may also be noted that the opaques forming the placer deposits are more concentrated in the surface samples than the samples collected from 40 cm depth.

This is well represented by samples 5 and 11 — both locations representing high energy condition and sample 11 located on the berm of a steep beach profile. According to Force (1991) large scale erosion plays a major part in the formation of placer deposits. Preservation of placers requires that the residuals of entrainment or erosion be prograded by net deposition without re-

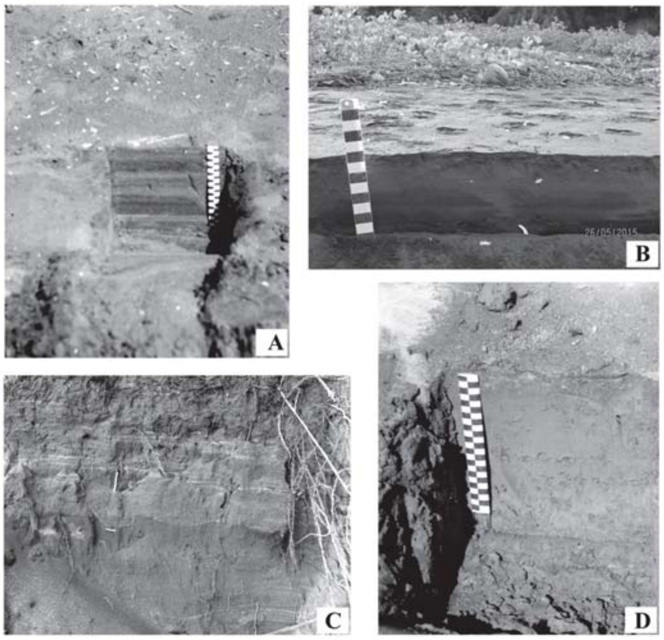

Plate 1A. Opaque-rich upper layers in beach, B) Concentration of black sand in the berm area, C) A trench cut in western part of the island showing sand layers overlain by course silt, D) Predominantly island clay rich layers in the bay-margin mixing. On beaches exceptional enrichment occur on erosionally steepened beach profiles that form during storm season (Force, 1991). The beach-derived concentrate once blown into the aeolian environment, is relatively safe from further marine erosion at the present sea level (Force, 1991). When the sediments of the LT zone are scanned, concentration of opaque minerals is found significantly low, except in the finest fraction of 4.25φ. A variation from 10% in 2.25φ to 83% in 4.25φ is indicating a strong wave action disallowing the settling of even denser grains in this zone (Table 3).

The percentage of zircon near the HHTL in the 3.75 φ fraction continuously decreases from north (50%) to south (2.2%), following the drift direction. with the exception of sample 11 collected from the berm area of southern beach. The samples near HHTL also show an increasing trend in the percentage of kyanite and pyroxenes from north to south. High order of kyanite present in this stretch may be presumed as the maxima of shoreward migration of sediments to this point in the centre of the beach stretch where deposition is more or otherwise a divergence of wave refraction may bring lighter, coarser materials along with finer heavy minerals. The dense granular particles of zircon (sp. gravity 4.7) in the 3.75 φ size fraction also decrease in concentration towards the LLTL. The samples taken from berm indicate the presence of high proportion of relict sediments indicated by the presence of significant percentage of kyanite, garnet, tremolite and zircon. The amphibole group shows low to moderate percentage of occurrence in the HHTL samples.

The LT samples show relatively more diversity than the HT samples. The presence of flaky constituents like chlorite, muscovite and biotite in greater percentage only in 2.25φ fractions together with denser grains of zircon and epidote in the 3.75 φ fraction characterise the low tide samples. This also supplements a strong winnowing action for the removal of lighter fine sediments from the LT level (Fig. 5a, Plate 1A and B).

Samples from the extended portion of the spit

The hydrodynamics of the extended portion of the spit is markedly different from that of the beach. Except for the western margin, the swash-backwash effect is totally absent. This portion of the spit is bounded by the main inlet at its southern end and two breach-channels cut across the spit, transferring water and sediment towards the bay during flood tide condition. This zone indicates the presence of high order of current ripples that shows that the effect of hitting waves are much nullified. Samples 22 and 24 were collected from relatively elevated portions of the spit which get exposed during ebb tidal conditions and samples 23 and 25 were collected from the bed of breach channels. Sample 25 is near the eastern margin of the spit, facing the bay. Majority of the samples are moderately well sorted, with mean grain size varying between 1.45φ and 2.80φ. This is relatively coarser than the beach samples. Unlike the beach samples the percentage of opaque minerals are generally low in this area, even in the finer fractions of 3.75 φ (16 to 32%). The opaque percentage increases to 50% in sample 23, probably owing to greater depth the opaques get concentrated at the bottom of the breach channels (Table 3). Once deposited at the channel bed these heavy grains are not re-suspended by the low energy ebb current. The presence of flaky minerals like chlorite, biotite and muscovite in both the coarser and finer fractions indicate a relatively low energy environment compared to the beach.

The percentage of pyroxene shows marked concentration on the elevated portions of the

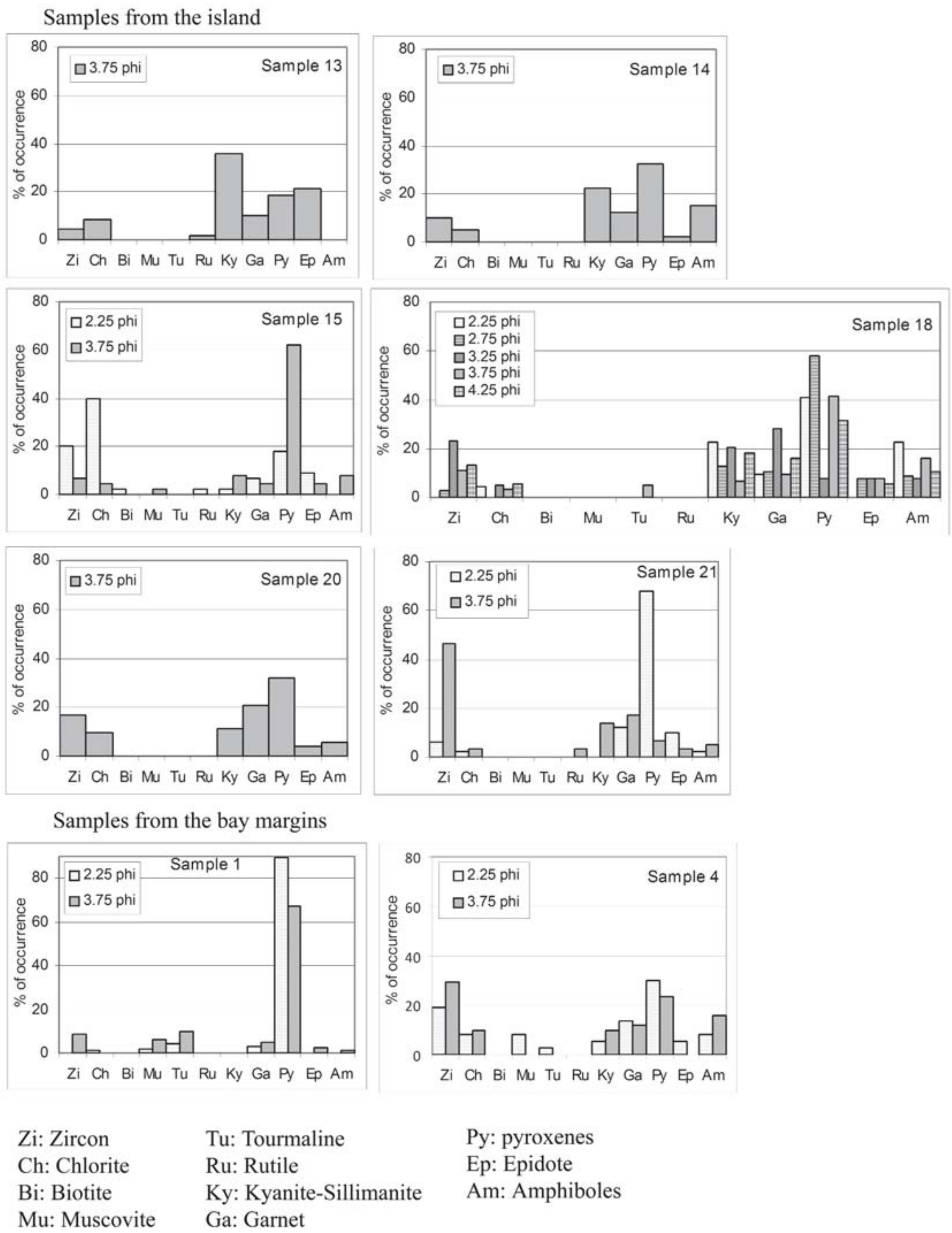

Figure 5b. Heavy mineral assemblage of island and bay-margin samples

spit even in the coarsest fraction of 2.25φ, but decreases drastically in the breach channels, where the amphiboles gain prominence. This may be attributed to the low preservation potential of the pyroxenes and a better capacity of amphiboles to endure weathering. Towards the bay ward margin of the spit sample 25 exhibits very low percentage (6.3%) of pyroxenes in the 3.75 φ size fraction, but kyanite, garnet, epidote and zircon show relatively higher percentage. Presence of flaky minerals even in finer fractions together with fine granular minerals towards the bay ward margin can explain the moderately sorted character of this sample. The minerals though transported to the bay ward margin through the breach channels during high tide cannot be further sorted when tide recedes (Fig. 5a).

Island samples

The samples from the western margin of the island were collected along two transects. Sample 13 and 14 were collected along the first transect starting from the island edge bordering the northern arm and samples 15, 18, 20 and 21 were taken along the second transect aligned almost west to east from bay ward margin to the interior. In general the mean grain size becomes finer towards the interior (2.88φ to 3.04φ) with moderate sorting. The finer samples with mean grain size above 4.0φ are very poorly sorted.

The opaque percentage increases in the fine fraction of 3.75 φ from 39.08% in sample 13 to 64.52% in sample 14 towards the interior. This may indicate the effect of deposition by the highest tide during monsoon along the northern arm of the bay. The distribution of opaques along the second transect is more interesting. Here the percentage of opaques in the coarse fraction of 2.25φ decreases from 70.51% (sample 15) to 62.96% (sample 18) as one move from the bay ward margin to interior. This may be attributed to the flow character in the bay. The water during the spring tide rides over the bay-mouth spit and enters the bay, where the flow gets bifurcated into the northern and southern arms. The deposition of the coarse grained opaques in high percentage at sample 15 and 18 may be attributed to this sudden reduction in velocity due to bifurcation of flow, which does not allow the coarse heavies to be entrained further (Table 3). The distribution pattern in the finer fraction represents just the reverse trend, i.e. increase in percentage as one moves towards interior.

The island samples show an unusual concentration of kyanite, garnet and zircon in the 3.25φ fractions, where the pyroxenes coming mainly from the Trappe rocks shows a low percentage in 3.25φ. The minerals of flaky nature are found in higher proportions in the coarser fractions. It is clear in sample 18 (where all the size classes have been analysed) that the pyroxenes, kyanite, garnet and amphiboles show abundance in 2.25φ and 2.75φ fractions. Then the same mineral assemblage shows high percentage of occurrence only in 4.25φ; the fraction which generally gets entrapped between coarser grains during entrainment and deposition. The differential distribution of flaky minerals either in the coarser end or in the finest end brings out the impact of advancing and withdrawing currents. The near-absence of zircon in the 2.25φ fraction clearly corroborates the trend that only the finer fractions of denser minerals are carried towards the interior part. The increasing concentration of zircon in the finer fraction of 3.75φ from 6.7% in sample 15 to 46.6% in sample 21 explains that whatever distance the zircon grains are pushed inside, remains the extreme point up to which the mineral advances during flood tides of monsoonal conditions (Fig. 5b, Plate 1C and D).

The bay margin samples

Four samples — Sample 1, 2, 3 and 4, collected from the bay margins, show an overall absence of course to medium sand. These samples are very poorly sorted with their mean grain size around 6.3 – 6.4φ. It should be mentioned here that Samples 1 and Sample 4 had 53.84% and 28.85% silt and clay fractions respectively. But for heavy mineral analysis only the sand-sized fractions were taken into consideration. Sample 1 was collected from the eastern bay margin. This sample shows an overwhelming dominance of pyroxenes (79%), both in the coarser (2.25φ) and finer (3.75φ) fractions. The sample site is located very near the mouth of the Galsure stream, draining into the bay from the eastern bay catchment area. It is the largest stream which drains into the Shrivardhan bay. Being a sheltered zone the area is free from wave impact and tidal current is responsible for depositing the finest particles at this location. Presence of flaky minerals of chlorite and muscovite in the coarser fraction together with finer fractions (3.75φ) of granular minerals like zircon, tourmaline and garnet may be explained by the entrainment equivalence of these minerals. Occurrence of rounded zircon and tourmaline in the finer fractions may mark the landward limit of sediment transfer from the offshore zone. Flood tides during monsoonal conditions may push the sediments to this location, which the retreating tides were not capable of carrying back. Very low percentage of opaques, in contrast to an otherwise opaque-rich coast also corroborates a low energy depositional environment (Table 3).

Sample 4, collected from the southern bay margin show greater diversity in mineral assemblage. Appreciable percentage of opaques (63%), in the coarser fraction of 2.25φ indicates a strong influence of the flood tide. The samples show co-existence of finer fractions of zircon (3.75φ) with the coarser fractions (2.25φ) of pyroxenes, almost having equivalent percentage (c.29%). Majority of the minerals coming from non-basalt sources show greater percentage of occurrence in the finer, than in the coarser size class. Compared to the island samples, minerals like kyanite, garnet or epidote show lesser percentage, which may indicate a relatively protected depositional environment adjoining the southern arm of the bay (Fig. 5b).

Interpretation:determining the provenance of the sediment

As far as the provenance of different minerals are concerned, it can be seen from (Table 5) that certain combination of mineral assemblage together with the characteristic crystal shape of some of the minerals like tourmaline and zircon are indicative of a particular source rock type. It may be seen from the table that the dominance of pyroxenes including high percentages of augite, hypersthene and opaques indicate basic igneous source rock (basalts), while the combination of garnet, kyanite, sillimanite and epidote point towards high-rank metamorphic source. Amphiboles may occur from metamorphics or even from granite and gneiss. Here rounded zircon and tourmaline indicate reworked sediment which may come from both acid igneous and metamorphics (Pettijohn, 1969). The principal factors which can modify the heavy mineral composition and distribution and limit the interpretation of assemblage in terms of the source area are — weathering and re-working of sediments including abrasion (Andel, 1959).

Before going into the interpretation of the

Table 4. Detrital mineral suites characteristics of source rock types (Pettijohn, 1969)

Reworked Sediments	Barite, Glauconite, Quartz (especially with worn overgrowths), chert, quartzite fragments, (orthoquartzite type), leucoxene, rutile, rounded tourmaline, rounded zircon.
Low-Rank Metamorphic	Slate and phyllite fragments, Biotite and muscovite, Feldspars generally absent, Leucoxene, Quartz and quartzite fragments (metaquartzite type), Tourmaline (small pale brown euhedra carbonaceous inclusions)
High Rank Metamorphic	Garnet, Hornblende (blue-green variety), Kyanite, Sillimanite, Andalusite, Staurolite, Quartz (metamorphic variety), Muscovite and Biotite, Acid lagioclase feldspar, Epidote, Zoisite, Magnetite
Acid Igneous	Apatite, Biotite, Hornblende, Monazite, Muscovite, Sphene, Zircon euhedra, Quartz of igneous variety, Microcline, Magnetite Tourmaline, small pink euhedra
Basic Igneous	Anatase, Augite, Brookite, Hypersthene, Ilmenite and magnetite, Chromite, Leucoxene, Olivine, Rutile, Plagioclase, intermediate Serpentine
Pegmatite	Fluorite, Tourmaline, typically blue Garnet, Monazite, Muscovite, Topaz, Albite, Microcline

samples it should be mentioned that, the heavy mineral assemblage of the samples collected from the Shrivardhan bay area, generally show limited diversity. Most of the samples have overwhelming percentage of opaques and augites (Table 5). However, since opaques can be derived from almost all types of source rocks, this group of minerals has not been taken into consideration while determining the provenance of the deposited materials.

As expected from a basaltic province, the percentage of pyroxenes (mainly augite) is high in all the samples, irrespective of its location (15–79%). Occurrences above 50% can be seen in eastern bay margin, the beach and also in southern spit area. In general, the percentage of pyroxenes increases towards the interior portion of the bay. According to Evans, Hayman-Majeed scale (Evans *et al.* 1934), majority of the locations show “abundant” to “very abundant” occurrences. Since augite is derived from the basic igneous rocks, and the entire catchment area is

Table 5. Order of persistence of detrital heavy minerals (Morton, 1984, cf. Pettijohn, 1941)

More stable	
Rutile	↑
Tourmaline	
Zircon	
Garnet	
Apatite	
Staurolite	
Kyanite	
Epidote	
Amphibole	
Andalusite	
Sphene	
Pyroxene	
Sillimanite	
Olivine	
Less stable	

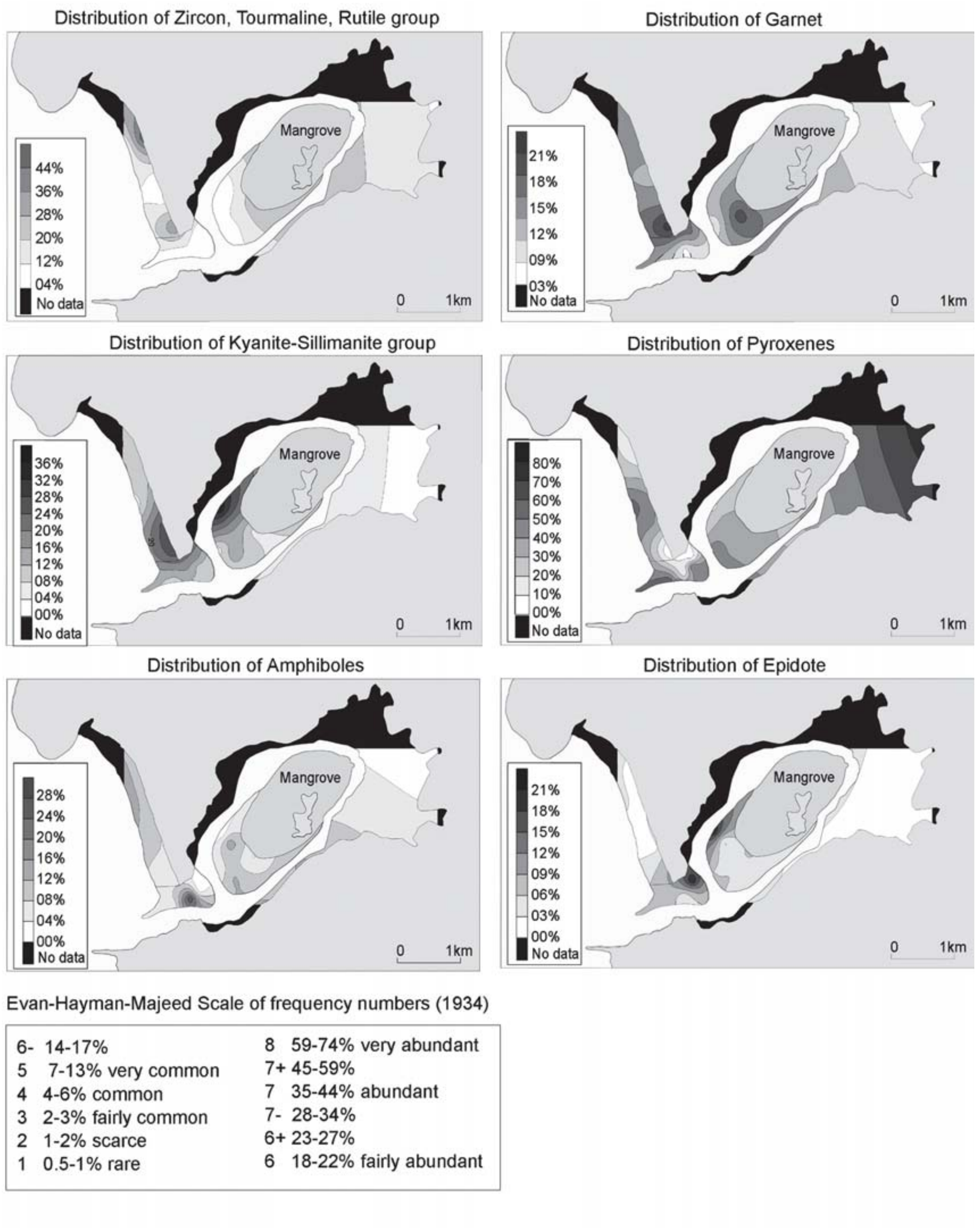

Figure 6. Distributional pattern of heavy minerals in Shrivardhan bay

composed of basalt one may infer a dominant supply from the bay catchment. However, it has to be kept in mind that in the western continental shelf sediments there is an influx of hornblende, pyroxene and muscovite. High concentration of pyroxene may be attributed to the overwhelming abundance of Deccan trappes (Siddiqui and Mallick, 1972). Hence, material derived from the erosion of the shelf or the headlands can also contribute to the supply of Pyroxenes (Fig. 6).

In general presence of kyanite-sillimanite group is “fairly abundant” to “abundant” (23–36%) in the western part of the island (sample 13), the berm area (sample 10 and 11). The kyanite/ sillimanite assemblage is “very common” (7–16%) in the samples from the southern portion of the bay-mouth spit (sample 22–25) and those from the northern beach (sample 7). It may be noted that the samples collected from the southern spit (sample 24, 25) also show appreciable proportion of Epidote (10–21%) and amphiboles (13–29%) (Fig. 6).

The distribution pattern of garnet is interesting. The percentage of occurrence of garnet increases towards southern beach, attaining maximum concentration in the berm area (23% in sample 11). The concentration also increases towards the interior part of the Central Island (21% in sample 20). The percentage drastically falls towards the eastern bay margin. This pattern is closely followed by the zircon-tourmaline-rutile group (ZTR), which shows maximum concentration of 36–50% in the beach HT samples (sample 5, 6 and 11), 28% in the samples from the interior portion of the Central Island (sample 21) and 26% in the southern bay margin (sample 4). In these locations Zircon is “abundant" to "very abundant" (Evans et al 1934) (Fig. 6).

From the heavy mineral assemblage it can be seen that majority of the minerals are from non-basalt sources like high-grade and low-grade metamorphics and acid igneous rocks. Since none of these occur in the catchment area of the bay these minerals must have been derived from other areas lying along the coast. The regional longshore drift in that case will be instrumental in carrying the materials to the vicinity of the bay, whereby these can be carried further inside by the local beach drift and tidal inflow. The dominant regional drift direction is from north to south during the monsoon months, but during the winter months a south to north reversal is reported (Kunte and Wagle, 2001). The nearest source of metamorphic minerals may be the Kaladgis. The Kaladgi quartzites and shales occur in southern Konkan, in numerous detached inliers. A cluster of inliers occurs along the banks of the streams and at Malvan, a patch of these Kaladgi beds juts into the sea (Gujar, 1995, Gazetteer, 1996).

Thus it can be deduced that majority of the material brought into the bay are brought in by marine processes.

The heavy mineral assemblage found in the study area can be broadly grouped into three 1) the zircon, tourmaline, rutile (ZTR) group, 2) the kyanite-sillimanite, garnet, amphibole, epidote group and 3) pyroxene group. The ZTR group indicates more stable minerals which can be considered as mineralogically matured. These minerals also have relatively high specific gravity (3.0 to 4.7) as compared to the other groups of minerals. The groups of minerals including kyanite, pyroxene, amphibole and epidote can be considered as mineralogically less matured (Morton, 1984, Table 5). However, the stability sequence of heavy minerals must take into account the possible differences in relative stabilities of minerals in different diagenetic environments (Morton, 1984).

From Figure 6 it can be seen that in most of the samples, the combined percentages of kyanite, pyroxene, amphibole and epidote are relatively high than the combined percentage of the ZTR group. Since minerals like kyanite, pyroxene and epidote tend to degenerate and become altered through the passage of time, the sediments in the Shrivardhan bay can be considered as relatively young and mineralogically immature. This can indicate that the process of sedimentation in the Shrivardhan bay area is still in progress.

Figure 6 shows the percentage variations of each mineral in the different morphological units. However, the combination of Zircon, Tourmaline and Rutile (ZTR) is relatively high only in the samples from the interior parts of the island and the southern bay margin. The relatively high proportion of ZTR indicates that the sediments from these areas are mineralogically more matured than those from other morphological units. This would mean that the process of sedimentation started earlier in the interior of the island and the bay-margin areas, where as the process of active sedimentation is continuing in the beach, southern spit and western parts of the island.

Conclusion

Heavy mineral analysis of the sediment collected from different morphological units of the beach, island and bay margin areas indicates that all the samples (in the selected size range) have significant contribution from high rank metamorphic rocks and also from Deccan basalts. Since the bay catchment and even the shore platform are composed of basalt, contribution from basaltic rock is expected. But contribution from high-grade metamorphics in the selected coarser fractions indicates that these materials have an immediate offshore source and are brought in by the wave and long shore drift. Basaltic minerals can come from both terrestrial and near shore zones. Since terrestrial contribution of water is relatively restricted to only the monsoon months, it can be stated that the source of the immature, fresh sediment is mostly from offshore sources. The tidal influence, the coastal streams draining into the bay and probable change in sea level may have acted in conjunction to affect the overall siltation process.

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References

Andel, Tj.H. van (1959) Reflections on the Interpretation of Heavy Mineral Analyses, *Journal of Sedimentary Petrology*: 29(2): 153–163.

Brűckner, H (1987) New data on evolution of Konkan (Western India) in Datye, V. S, Diddee, J, Jog, S.R and Patil, C.J (eds) *Explorations in the Tropics*, (Prof. K. R. Dikshit felicitation volume), Pune: 173–184.

Evans, P., Hayman, R. and Majeed, M.A. (1934) The graphical representation of heavy mineral analysis, *Quaternary Journal of Geological, Mining and Metallurgical Society of India*: 6(2): 27–47.

Force, E. R. (1991) Placer deposits, Sedimentary and diagenetic mineral deposits: a basin analysis approach to exploration, *Review in Economic Geology*, Society of Economic Geologists, University of Texas, USA. 5: 131–140.

Friedman, Gerald M. (1961) Distinction between dune, beach and river sands from their textural characteristics, *Journal of Sedimentary Petrology*, 31(4): 514–529.

GoM (1996) Govt. of Maharashtra, *Gazetteers of* *the Bombay Presidency, Ratnagiri and Savantvadi*, Facsimile reproduction of original printed edition 1880. Gazetteer Department, Mumbai: 506p.

Gujar, A.R. (2002) Status of placer exploration in India in Chandrashekhar, N. and Subramanian, P. (eds) *Proc. National Conference on Exploration, Mining and Processes of Beach Placer in India*: 10–19.

Gujar, A.R., Angusamy, N, and Rajamanickam, G. V (2007) Characterization of Opaques off Konkan Coast Maharashtra, Central West Coast of India, *Journal of Minerals & Materials Characterization & Engineering*, USA, 6(1): 53–67.

Gujar, A.R., Ambre, N.V., Mislankar, P.G. and Iyer, S.D. (2010) Ilmenite, Magnetite and Chromite Beach Placers from South Maharashtra, Central West Coast of India, *Resource Geology*, 60(1): 71–86.

Gujar, A.R., (1995) Morphogenetic controls on the distribution of the littoral placers along central west coast of India in Desai, N.; Ganapathi, S (eds) *Proc. of National. Symposium on Recent Researches in Geology of Western India; Baroda*; India: 171–180.

Komar, P.D (2007) The Entrainment, Transport and Sorting of Heavy Minerals by Waves and Currents , in Mange, M. and Wright, D. (eds) *Heavy Minerals in Use*, Developments in Sedimentology Series. Elsevier, Amsterdam, Netherlands. 58: 3–48

Kunte, P. and Wagle, B.G. (2001) Littoral transport studies along West Coast of Idnia — A review. *Indian Journal of Marine Sciences*. 30(June): 57–64.

Ly, C.K. (1981) Sources of beach sand from the central and eastern coasts of Ghana, West Africa, *Marine Geology*. .44(3/4): 229–240.

Mallik, T.K. (2004) heavy mineral studies — their importance and implications in Loveson, V.J. (ed) *Proc. of National Workshop and Seminar on Sustainable Development of Coastal Placer Minerals*, Allied Publishers: 308p.

McDowell, D. M and O’Connor, B. A (1977): *Hydraulic Behaviour of Estuaries*, Pub. The Macmillan Press Ltd, London, 132p

Morton, A.C. (1984) Stability of detrital heavy minerals in Tertiary sandstones from North Sea basin. *Clay Minerals*. 19. 287–308.

Pettijohn, F.J. (1941) Persistence of heavy minerals and geologic age. *Journal of Geology*. 49, 610–625.

Pettijohn, F.J (1969): *Sedimentary Rocks*, Harper and Row, New York, 718p.

Rajamanickam, G.V. (2001) *Handbook of Placer Mineral Deposits*. New Academic Publishers, New Delhi: 327p.

Ramasamy, P. and Karikalan, R. (2010) Distribution and Percentage of Heavy Minerals in Coastal Geomorphologial Landforms in Palk Strait, Southeast Coast of India. *Middle-East Journal of Scientific Research*. 5(1): 49–53.

Rittenhouse, R. (1943) Transportation and deposition of heavy mineral, *Geological Society of America Bulletin*, 54(12): 1725–1780.

Rivas-González M. and Roa Morales, P. (1993) Environment parameters of sediments and the interface sediment – water in the Tacarigua lagoon (Venezuela), *Coastal Zone*: 3435–3458.

Savant, P.T (1980) *Geological Studies of the Coastal Tract Between Alibag and Srivardhan, Kolaba District, Maharashtra, India*, Unpublished PhD Thesis, University of Poona.

Shuisky, Y. D. and Schwartz, M.L. (1983) Basic principles of sediment budget study in the coastal zone, *Shore and Beach*, 34–40.

Siddique, H.N. and Mallik, T.K. (1972) An analysis of the mineral distribution pattern in the recent shelf sediments off Mangalore, India. *Marine Geology*, 12: 359–393.

Singerland,R. (1984) Role of Hydraulic Sorting in the Origin of Fluvial Placers, Journal of *Sedimentary Petrology*. 54(1): 137–150.

Wilde, Pat and Case, Charles, W (1977): Techniques for predicting sediment transport in the marine environment using natural heavy mineral tracers, *Shore and Beach*. 45(2): 25–29.

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