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**Heavy Mineral Placer Deposits of Ekakula Beach,
Gahiramatha Coast, Orissa, India**

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Abstract: Ilmenite, hematite, garnet, monazite, zircon, rutile, magnetite, sillimanite, pyroxene and amphibole from the beach sands of Ekakula, Gahiramatha coast, Orissa, India are reported here for the first time. Their total concentration varies from 26.4 to 100%. Ilmenite, monazite and zircon are between 100 and 300 μm in size and are well rounded in shape. Ilmenite-hematite intergrowth is common. Ilmenite has 50.02–54.73% TiO_2 , 42.42–46.90% FeO (total Fe) and small amounts of Al, Mn, Mg, Ca, Ba, Si, V, Cr, and Zn. The bulk samples contain 10.63–41.42% TiO_2 , 6.15–26.07% FeO , 5.86–16.75% Fe_2O_3 , 7.41–61.74% SiO_2 , 1.39–12.83% Al_2O_3 , 0.32–4.97% CaO , 0.53–4.24% P_2O_5 , 0.17–3.27% MgO , 0.15–2.97% Na_2O , 0.07–2.34% K_2O , and 0.05–0.71% V_2O_5 together with appreciable amounts of La, Ce, Pr, Nd, Sm, Eu, Y, U, Th, Zr, and trace amounts of Pb, Zn, Cu, Ni, Co, and Cr. Khondalite, charnockite, calc-silicate granulite, leptynite, migmatite, gneiss, basic granulite and pegmatite of the Eastern Ghats appear to be the major source for the above heavy mineral assemblages. The samples are amenable to gravity and magnetic methods of beneficiation.

1. Introduction

Titanium minerals are exploited and processed mainly for the production of pure titanium oxide for use in paint industry as pigment which is the largest application of titanium. It is gaining importance as it is found replacing steel, and alloys of copper and aluminum in many engineering applications. The increase in the use of titanium is attributed to its outstanding erosion and corrosion resistance, high specific strength, and good fracture toughness. It has a wide range of alloying behaviour, and this makes it possible to alloy titanium with aluminium, vanadium, palladium, molybdenum, tin, zirconium, silicon, and chromium for obtaining much higher strength as well as for building superior resistance to chemical attack. Titanium is the ninth most common element in the earth's crust and occurs mainly in the form of oxides of which ilmenite (FeTiO_3) and rutile (TiO_2) are very common. India has an estimated reserve of 188.4 million tonnes of ilmenite and 9.8 million tonnes of rutile (Dwivedy, 1995) against the world reserve of 430 million tonnes of ilmenite and 170 million tonnes of rutile (Indian Bureau of Mines, 1997). In India, ilmenite and rutile form constituents of beach sand deposits found right from Ratnagiri coast in the west to Orissa coast in the east (Ramamohana Rao et al., 1983; Ali et al., 1989; Sengupta et al., 1990; Sukumaran and Nambiar, 1994). But the minerals are concentrated in three well defined zones: (a) A stretch of 22 km between Neendakara and Kayamkulam, Quilon district,

Kerala contains 65–85% heavy minerals (b) A stretch of 6 km from mouth of Valliyar river to Colachal in Manavalakurichi, Kanyakumari district, Tamilnadu, where the heavy minerals in the beach sands vary from 50 to 70% (c) In Chhatrapur coast stretching a length of 18 km in Ganjam district, Orissa, contains heavy minerals varying between 18 and 23% (Indian Bureau of Mines, 1997).

Heavy mineral assemblages comprising of ilmenite, hematite, sillimanite, garnet, rutile, monazite, zircon, amphibole, clino- and ortho-pyroxene, epidote, and zoisite are also associated with the sediments (silty clay, sand-silt-clay, and clayey silt) in the inner shelf off Orissa coast. Concentration of these heavy minerals show preference to medium sand in comparison to fine or coarse sand (Sengupta et al., 1992).

The occurrence of heavy minerals in beach sands of Ekakula, Gahiramatha coast, Orissa, India is reported here for the first time. A 35 km beach runs northeast to southwest separated from the mainland by mangroove creeks. This beach is well known in the world due to mass nesting of Olive Ridley turtles. The present investigation is restricted from Habalikhathi to Ekakula in north eastern direction and the surrounding small islands (Fig. 1), e.g. Babubali (Small wheeler), Nadiachadha (Coconut wheeler), and Tentuliachadha (Outer wheeler). The Ekakulanasi (tip) got separated from the mainland in a cyclone in May 1989.

2. Mode of Occurrence and Mineralogy

The heavy minerals are concentrated in Ekakula beach stretching for about 8 km in length. The slope of the beach is not uniform and varies from gentle to very steep. The breadth of the beach varies between 52 and 200 m. In some places, the heavy minerals are highly concentrated (more or less heavies only), the thickness of which varies

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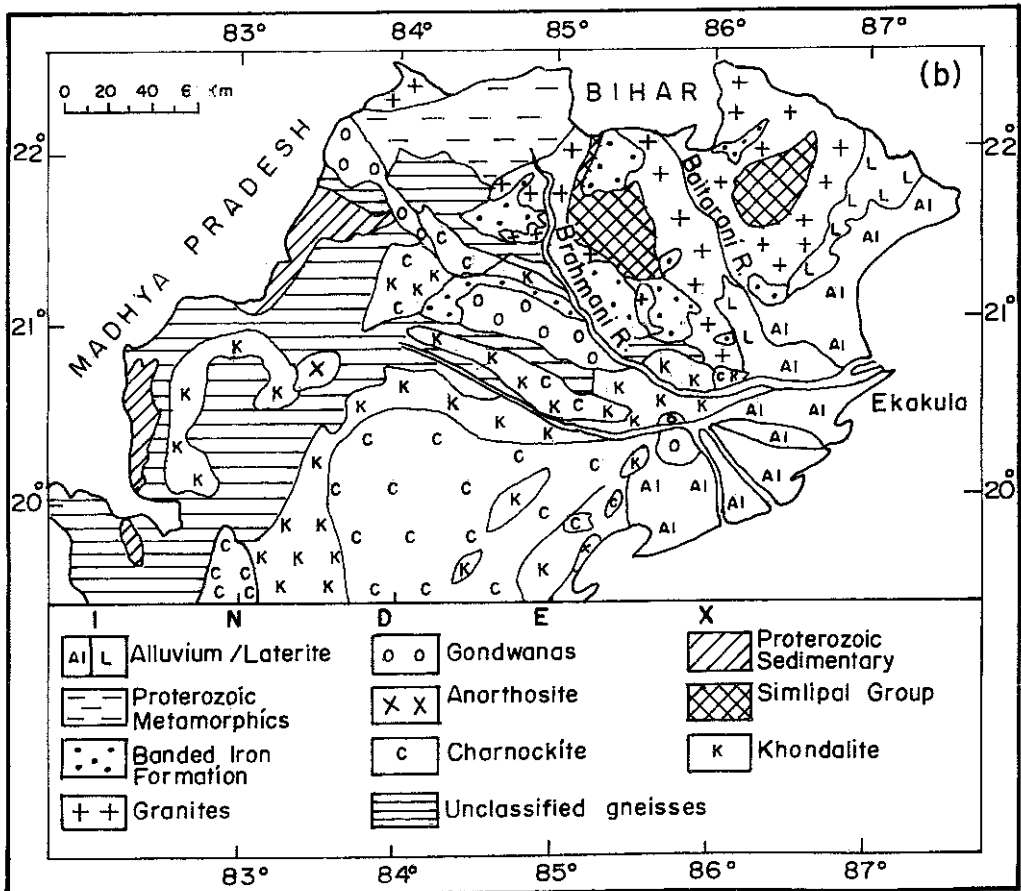
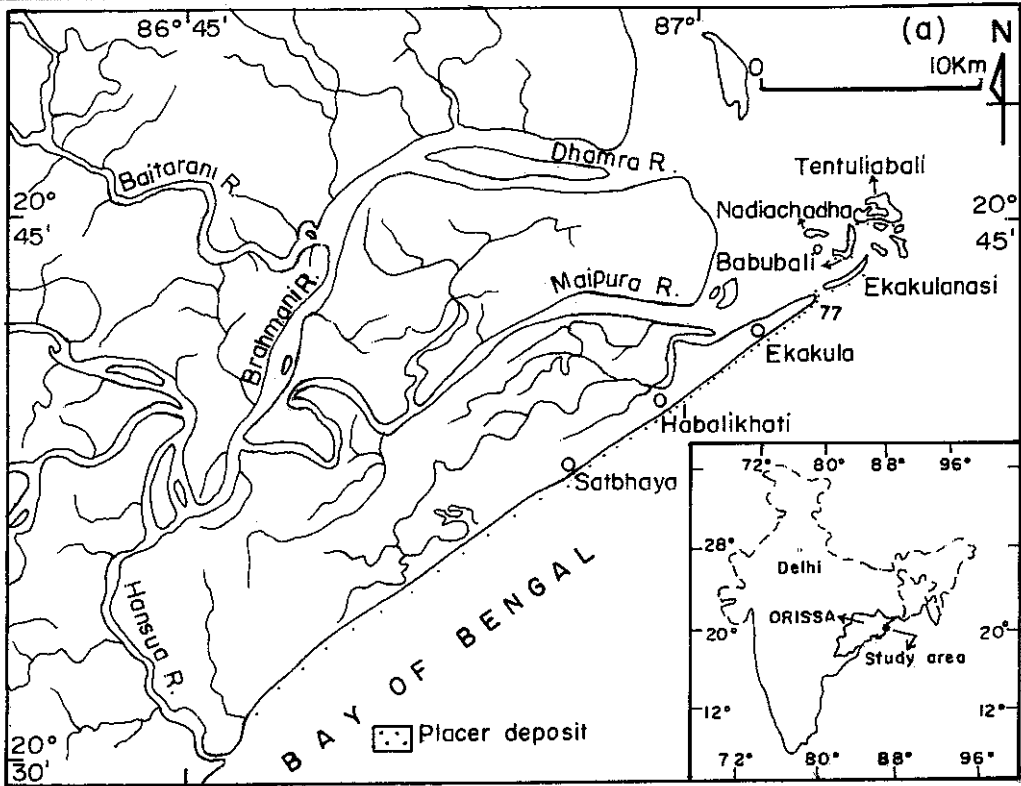


Fig 1 a: Location map of the area around Gahiramatha coast b: Geological map of part of Orissa (modified after Mahalik, 1995) showing the catchment area of rivers Brahmani and Baitarani

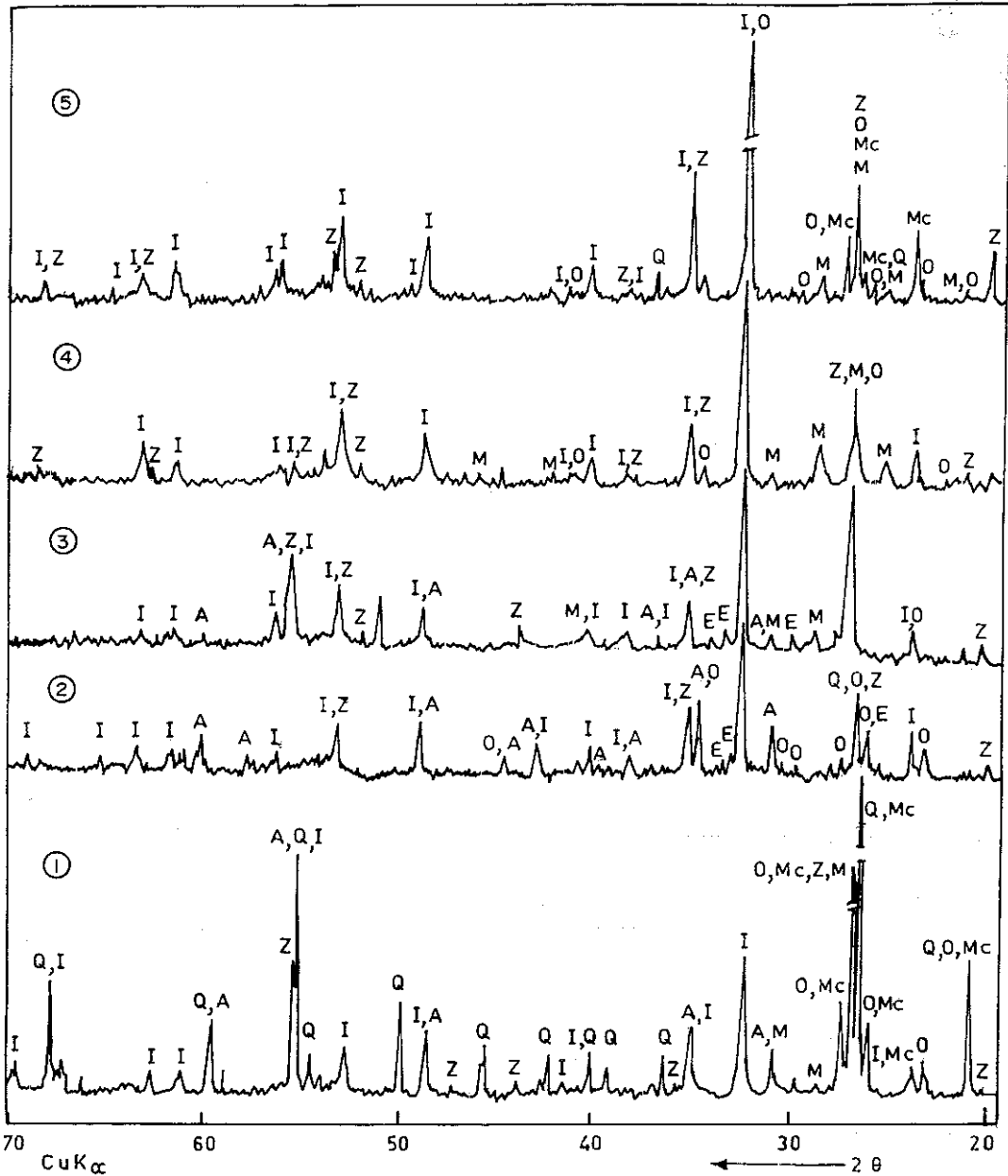


Fig 2 X- ray diffraction patterns of beach sand samples, Gahiramatha coast.

I= ilmenite, M= monazite, Z= zircon, Q= quartz, O= orthoclase, Mc= microcline, A= almandine, E= epidote
 Location : 1= Ekakula tip river side, 2= Babubali, 3= Ekakula No 64, 4= Ekakula No 53, 5= Ekakula No. 38.

from 5 to 30 cm. The heavy minerals are also found either as discrete grains or as alternate stratified layers up to 3-5 m depth both in the beach and 500 m away from beach towards inland. For the sake of convenience, the sampling points are numbered in increasing order from Habalikhathi (No 1) at an interval of 100 m towards Ekakula (Ekakula tip is numbered 77). The samples are collected from the beach up to the mid-tide water level, mixed thoroughly and then the representative samples were taken for mineralogical and geochemical studies. The samples were separated into light and heavy fractions using bromoform.

On microscopic as well as XRD examination, the samples revealed that they are constituted of ilmenite with minor amounts of monazite, zircon, garnet, magnetite, hematite, rutile, sillimanite, epidote, anthophyllite, hornblende, and pyroxene together with quartz, orthoclase, and microcline (Figs. 2 and 3). The heavy minerals are finer in size than the quartz-feldspar grains comprising the lighter minerals. More or less similar occurrences of heavy mineral assemblages have been reported from the east coast beaches of Tamilnadu, Andhra Pradesh (Ramamohana Rao et al., 1983; Nagamalleswara Rao,

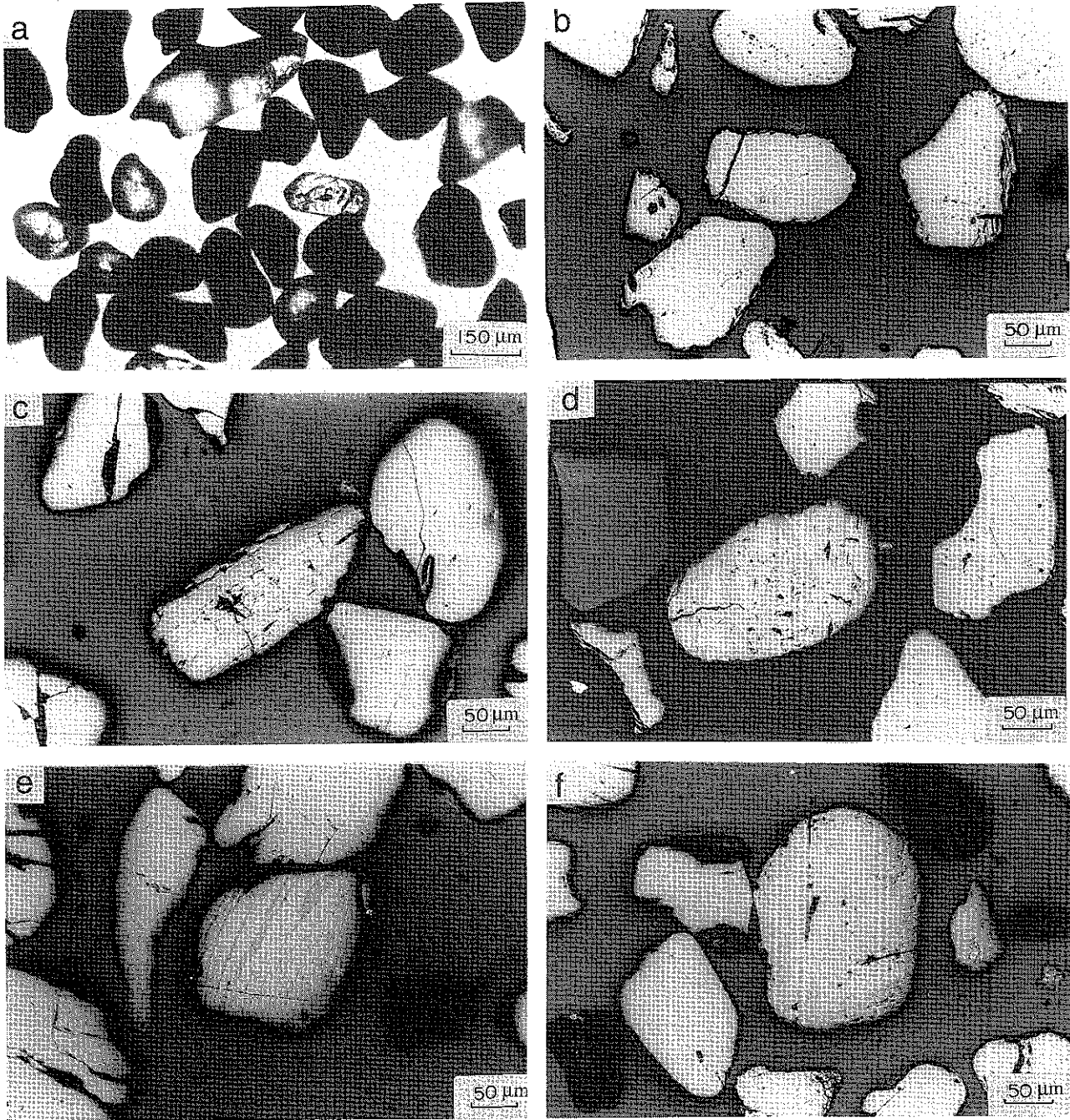


Fig 3 Photomicrographs of heavy sand minerals

- a: Grains of ilmenite (black), monazite (subrounded, dark grey), zircon (euhedral with zoning) and garnet (subangular elongated at top centre)
- b: Highly irregular exsolved hematite (white) within ilmenite (grey) is seen at the central grain. The associated grains are ilmenite and hematite
- c: Ilmenite grains mounted in epoxy resin. Laths of ilmenite (grey) in hematite (white) shows banded intergrowth pattern
- d: Exsolved intergrowth of ilmenite (grey) in a host of hematite (white). The ilmenite laths contain fine streaks of hematite. Silicate grain is dark grey
- e: Ilmenite grains showing various shades of grey due to reflection pleochroism. The central grain exhibits enechelon flames of intergrown ilmenite within hematite host. Note the thickness variation in ilmenite lamellae which may represent two generations
- f: Anatase patches along margins and within ilmenite (grey) due to alteration

Table 1 Size analyses and heavy mineral distribution in beach sands of Gahiramatha coast.

Sample Nos.	Fraction	>500 µm	500-246 µm	246-124 µm	124-63 µm	Total
38B	Weight %	0.38	1.93	85.67	12.02	100.00
	Heavy %	0.07	1.17	82.93	11.65	95.82
42B	Weight %	2.38	7.30	79.34	10.98	100.00
	Heavy %	0.18	3.99	78.58	10.88	93.63
46B	Weight %	0.32	11.19	75.70	12.79	100.00
	Heavy %	0.10	5.66	74.49	12.36	92.61
50B	Weight %	0.72	5.81	78.02	15.45	100.00
	Heavy %	0.09	2.55	75.46	15.28	93.38
52B	Weight %	0.24	3.06	87.24	9.46	100.00
	Heavy %	0.04	1.69	85.43	9.46	96.62
53B	Weight %	0.00	0.40	69.59	30.01	100.00
	Heavy %	0.00	0.36	69.59	30.01	99.96
54B	Weight %	0.00	0.00	49.30	50.70	100.00
	Heavy %	0.00	0.00	48.95	50.19	99.14
58B	Weight %	19.52	49.71	24.25	6.52	100.00
	Heavy %	0.18	1.89	18.07	6.23	26.37
60B	Weight %	0.46	5.41	83.47	10.66	100.00
	Heavy %	0.04	2.98	82.41	10.52	95.95
62B	Weight %	4.42	26.87	48.98	19.73	100.00
	Heavy %	0.38	2.78	40.55	19.35	63.06
64B	Weight %	0.00	0.40	53.58	46.02	100.00
	Heavy %	0.00	0.40	53.58	46.02	100.00
66B	Weight %	0.57	8.16	67.32	23.95	100.00
	Heavy %	0.00	4.67	63.73	23.56	91.96
68B	Weight %	0.00	8.33	50.83	40.84	100.00
	Heavy %	0.00	4.02	42.22	39.93	86.17
70B	Weight %	0.27	2.26	86.40	11.07	100.00
	Heavy %	0.05	1.35	84.35	10.96	96.71
75B	Weight %	0.21	4.51	85.72	9.56	100.00
	Heavy %	0.07	2.44	85.07	9.44	97.02

Table 2 Size and shape distribution of different minerals obtained by Image Analysis System.

	Ilmenite %	Monazite %	Zircon %	Other Silicates %
Mean feret size (µm)				
0-50	0.00	0.00	0.00	0.00
50-100	0.00	1.26	0.00	0.00
100-150	15.88	32.91	15.79	7.72
150-200	46.83	40.51	55.26	27.94
200-250	26.07	18.99	21.05	27.21
250-300	8.52	5.70	5.26	18.01
300-350	2.11	0.63	2.63	11.40
350-400	0.44	0.00	0.00	3.68
400-450	0.07	0.00	0.00	1.84
450-500	0.00	0.00	0.00	1.47
500-550	0.07	0.00	0.00	0.36
550-600	0.00	0.00	0.00	0.00
600-650	0.00	0.00	0.00	0.36
Mean size	194µm	173µm	183µm	238µm
Maximum size	520µm	330µm	320µm	611µm
Minimum size	104µm	94µm	126µm	113µm
Shape (Form Factor)				
0.4-0.5	0.07	0.00	0.00	0.36
0.5-0.6	0.15	0.00	2.63	0.74
0.6-0.7	0.95	0.00	10.53	4.04
0.7-0.8	6.48	1.27	31.58	11.40
0.8-0.9	33.79	17.72	39.47	40.07
0.9-1.0	58.56	81.01	15.79	43.38
Mean F F	0.91	0.95	0.81	0.88
Maximum F F	1.00	1.00	0.99	1.00
Minimum F F	0.41	0.77	0.57	0.42

1994), and Chhatrapur, Orissa (Rao, 1989; Sengupta et al., 1990, 1992; Bhattacharya and Sengupta, 1994)

Ilmenite mostly occurs as subrounded to rounded grains. Sometimes it contains exsolved laths, streaks and irregular bodies of hematite (Fig. 3b). Hematite also contains exsolved bodies of ilmenite which may be laths, fine streaks or highly irregular patches (Figs. 3c-3e). The ilmenite (or hematite) lamellae thickness in hematite (or ilmenite) matrix show conspicuous bimodal distribution (Fig. 3e). Ilmenite-hematite intergrowth also gives rise to emulsion texture. Subrounded grains of rutile in trace quantities are also observed. Leucoxene and anatase occurs as patches along margin, fracture and within ilmenite due to alteration (Fig. 3f). In some rare occasions, ilmenite completely alters to anatase. Monazite grains are generally subrounded to rounded while the zircon grains are elliptical to subhedral. Often zircon occurs as well developed crystal with zoning. Garnet is angular to subangular and has conchoidal to subconchoidal fracture.

Grain size analyses of the samples along with their heavy mineral distribution in different size fractions (>500 µm; 500-246 µm; 246-124 µm; and 124-63 µm) are reported in Table 1. The samples are generally below

1 mm and do not contain silt and clay. In most cases, the bulk of the sediments are in the size range of 246-124 µm. It has been observed that the sediments are slightly finer grained towards north eastern end of Ekakula. But the sediments become again slightly coarser at the extreme end of Ekakula, where the geomorphology changes very frequently due to either the beach formation or the beach erosion. Total heavy minerals in the samples vary from 26.37 to 100%. In most cases, the heavies are around 90% and are concentrated below 246 µm size.

The grain size and shape of ilmenite, monazite, zircon and silicate gangue minerals are determined with the help of Image Analysis System (Leitz ASM 68k) attached to an optical microscope, and mean feret diameter and form factor*1 are reported in Table 2.

*1 Here "feret" refers to size of the mineral grains measured by Image Analysis System. The projections are calculated in angular steps of 7.5 degrees. Since a projection calculated every 7.5 degree, this is equivalent to 24 individual projections (7.5°×24=180°). The mean of the 24 individual projections is the mean feret diameter of the grains. The form factor refers to shape. It is a measure of how well a grain approximates a circle (in two dimensions). It has a definition range from 0 for a straight line to 1 for a circle, with corresponding intermediate values.

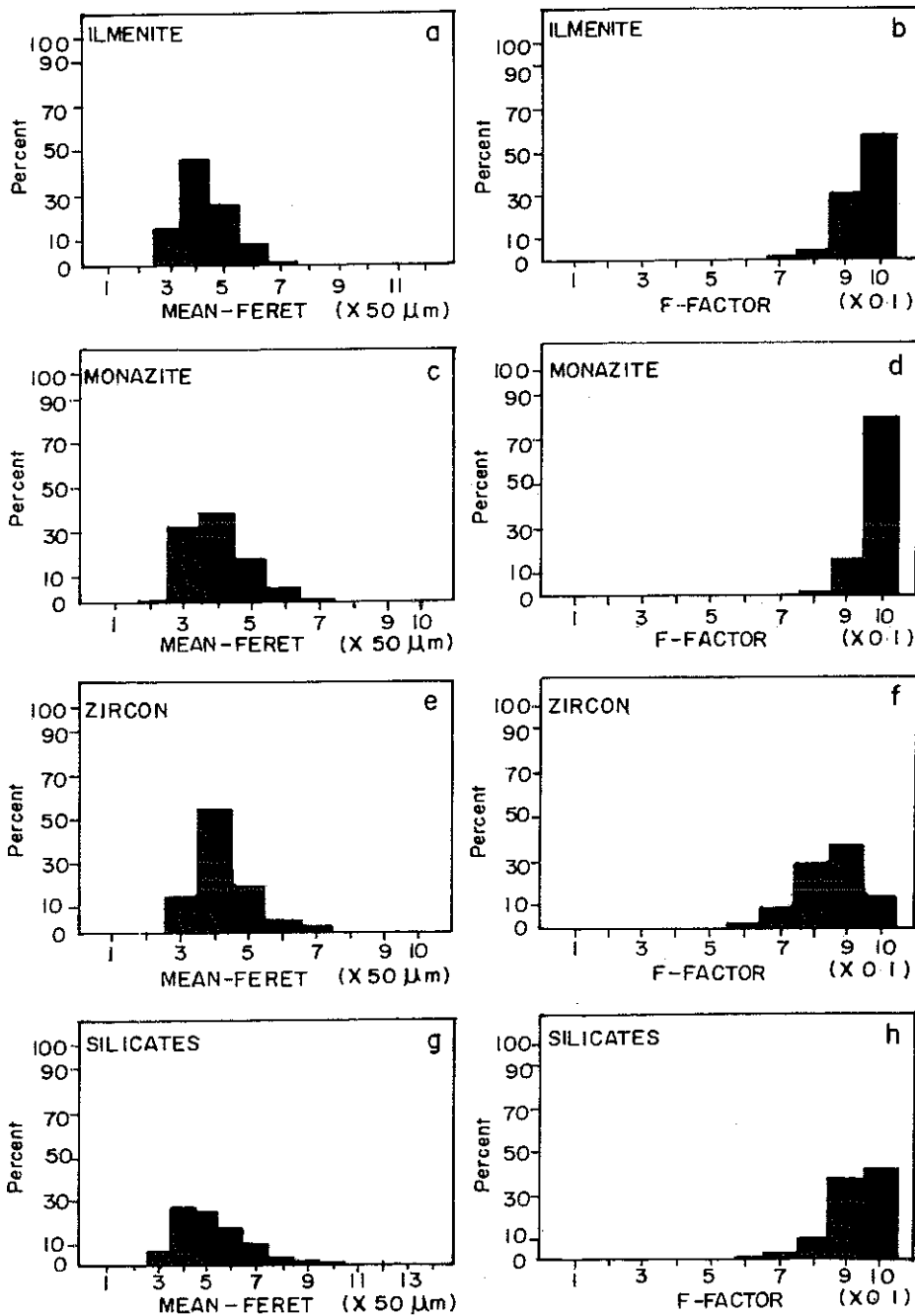


Fig 4 Size and shape distribution of different minerals. a-b: ilmenite, c-d: monazite, e-f: zircon, g-h: silicate gangues.

The ilmenite grains vary from 104 to 520 μm and show average mean feret diameter of 194 μm . Most of the ilmenite grains (97.3%) are found in between 100 and 300 μm (Fig. 4a) The shape (form factor) of the ilmenite grains are between 0.41 and 1. The majority of the ilmenite grains (92.35%) having form factor in the range of 0.8 to 1 (Table 2; Fig. 4b) together with the mean form factor value of 0.91 indicate their well rounded nature. Monazite grains are slightly finer than ilmenite grains and

vary in the mean feret size from 94 to 330 μm with an average of 173 μm . 98.11% of monazite grains show mean feret size in the range of 100 to 300 μm (Fig. 4c). The form factor of these monazite grains varies between 0.77 and 1 with an average value of 0.95. 98.74 and 81.01% of these grains are in the shape factor ranges of 0.8 to 1 and 0.9 to 1, respectively (Table 2; Fig. 4d). Hence, they are very well rounded. The zircon grains vary in mean feret size from 126 to 320 μm with an average value of 183 μm and their shape factor varies from 0.57 to 0.99 with a mean value of 0.81 (Table 2; Fig. 4e, f).

The silicate gangue minerals (quartz, feldspars, garnet, pyroxene, amphibole, epidote and sillimanite) on the other hand are slightly coarser varying in size between 113 and 611 μm with an average value of 238 μm . Their form factor varies from 0.42 to 1, but most of the grains (83.45%) have values between 0.8 and 1 indicating rounded nature. The distribution of mean feret size and form factor are given in Figure 4g, h.

The modal analyses of ilmenite, monazite, zircon and other silicate gangue minerals (calculated from the image analyses data) are 70.42%, 5.73%, 2.52% and 21.33% respectively.

3. Mineral Chemistry of Ilmenite and Hematite

Ilmenite grains as well as the ilmenite and hematite mineral phases from the ilmenite-hematite intergrowths were examined by electron microprobe using a JEOL, EPMA super probe JXA-8600 model, with a current of 2×10^{-8} A, and mineral standards (Structure Probe Inc., Canada), to establish the presence of various major, minor

Table 3 Electron microprobe analyses of ilmenite and hematite (wt %).

	Ilmenite													Hematite			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FeO*	42.81	45.43	45.16	45.46	44.91	44.77	46.32	46.90	44.92	44.65	42.42	45.14	43.98				
Fe ₂ O ₃ **														88.13	87.97	81.03	84.62
TiO ₂	54.73	50.02	50.99	52.97	52.61	52.25	50.77	50.45	52.39	52.62	53.30	53.92	51.67	10.22	10.50	16.29	13.14
SiO ₂	-	-	-	0.04	-	-	-	-	-	-	0.13	-	0.60	-	0.03	0.21	0.47
Al ₂ O ₃	0.23	1.63	1.53	-	-	0.02	0.01	-	-	-	0.09	1.59	1.80	0.15	0.20	0.65	0.17
MgO	0.55	0.11	0.11	1.02	0.56	1.28	0.63	0.80	0.97	0.88	0.12	0.19	1.68	0.04	Tr	0.39	0.43
MnO	0.20	1.21	0.99	0.51	0.45	0.29	0.27	0.19	0.29	0.42	1.78	0.28	0.10	0.22	0.22	0.03	-
CaO	-	0.01	0.01	-	-	0.01	Tr	-	0.02	-	0.01	Tr	-	0.01	0.03	-	0.02
Cr ₂ O ₃	0.19	0.29	0.03	0.09	0.04	-	0.05	-	0.07	0.26	0.02	0.01	-	0.19	-	0.38	0.18
ZnO	0.02	-	0.14	-	0.24	0.02	0.19	-	-	0.05	0.10	0.14	-	0.11	-	-	-
V ₂ O ₃	0.28	0.26	0.27	0.29	0.29	0.28	0.27	0.27	0.28	0.28	0.28	0.27	0.27	0.05	0.03	0.02	0.07
BaO	0.35	0.26	0.22	0.26	0.29	0.45	0.27	0.20	0.37	0.26	0.31	0.37	0.40	0.02	0.07	0.18	0.02
Total	99.36	99.22	99.45	100.64	99.39	99.37	98.78	98.81	99.31	99.42	98.56	101.91	100.50	99.14	99.05	99.18	99.12
	← On the basis of 6(O) →													← On the basis of 3(O) →			
Fe	1.787	1.931	1.908	1.896	1.900	1.892	1.988	2.014	1.900	1.883	1.798	1.845	1.810	1.719	1.715	1.541	1.626
Ti	2.054	1.912	1.938	1.987	2.002	1.985	1.959	1.948	1.993	1.997	2.032	1.982	1.912	0.199	0.205	0.310	0.252
Si	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.029	0.000	0.001	0.005	0.012
Al	0.014	0.098	0.091	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.006	0.091	0.104	0.005	0.006	0.020	0.005
Mg	0.041	0.009	0.008	0.076	0.042	0.097	0.048	0.061	0.073	0.066	0.009	0.014	0.123	0.002	Tr	0.015	0.016
Mn	0.008	0.052	0.042	0.021	0.019	0.012	0.012	0.008	0.013	0.018	0.076	0.011	0.004	0.005	0.001	0.001	0.000
Ca	0.000	0.001	0.001	0.000	0.000	0.001	Tr	0.000	0.001	0.000	Tr	Tr	0.000	Tr	0.001	0.000	0.001
Cr	0.007	0.012	0.001	0.004	0.002	0.000	0.002	0.000	0.003	0.010	0.001	Tr	0.000	0.004	0.000	0.008	0.004
Zn	0.001	0.000	0.005	0.000	0.009	0.001	0.007	0.000	0.000	0.002	0.007	0.005	0.000	0.002	0.000	0.000	0.000
V	0.011	0.010	0.011	0.011	0.012	0.011	0.011	0.011	0.011	0.012	0.011	0.011	0.011	0.001	0.001	Tr	0.002
Ba	0.007	0.005	0.004	0.005	0.006	0.009	0.005	0.004	0.007	0.005	0.006	0.007	0.008	Tr	0.001	0.003	Tr
Total	3.930	4.030	4.009	4.002	3.992	4.009	4.033	4.046	4.001	3.993	3.952	3.966	4.001	1.937	1.931	1.903	1.918

* Total iron as FeO; ** Total iron as Fe₂O₃; Tr = trace; - = not detected; Ilmenite (2,3) - Hematite (14,15) and Ilmenite (13) - Hematite (16,17) form intergrowth pairs

and trace elements in them. The analyses of ilmenite and hematite together with their structural formulae are reported in Table 3. Ilmenite analyses from Gahiramatha coast indicate 42.42–46.90% FeO (total iron) and 50.02–54.73% TiO₂. Besides, they contain up to 1.80% Al₂O₃, 0.10–1.78% MnO, 0.11–1.68% MgO, up to 0.60% SiO₂, 0.20–0.45% BaO, 0.26–0.29% V₂O₃, up to 0.29% Cr₂O₃, and 0.24% ZnO, and trace amounts of CaO. Mg and Mn in ilmenite may be due to substitution for Fe²⁺.

The intergrown hematite laths and bands in ilmenite contain 81.03–88.13% Fe₂O₃. It is interesting to find that these hematite laths and bands contain high amounts of titanium (10.22–16.29% TiO₂) which may be due to the presence of microcrystallites of ilmenite and/or solid solution of Fe₂O₃ and FeTiO₃. Small amounts of Al₂O₃ (0.15–0.65%), SiO₂ (trace to 0.47%), MgO (trace to 0.43%), BaO (0.02–0.18%), and V₂O₃ (0.02–0.07%) are present in the analyses. Cr, Mn and Ca are also present in some of the hematite analyses. Among ilmenite and hematite in the ilmenite-hematite intergrowths, Al₂O₃, MgO, MnO, V₂O₃, and BaO are relatively more

in the ilmenite phase than those in the hematite.

4. Chemistry of Beach Sand Samples

Thirteen bulk beach sand samples along with ten heavy fractions separated by using bromoform (more or less similar to the natural, mechanically concentrated heavy mineral sands) were analysed for TiO₂, Fe₂O₃, FeO, SiO₂, Al₂O₃, MnO, CaO, MgO, V₂O₃, K₂O, Na₂O, and LOI by conventional wet chemical methods. Trace elements like Pb, Zn, Cu, Co, and Cr were analysed by Varian Tectron AA-1475 ABD Atomic Absorption Spectrophotometer. A few samples were also analysed for REE and radioactive elements by NAA (Neutron Activation Analysis). The major, minor, trace, REE, and radioactive elements in the samples are reported in Table 4. The bulk samples are dominantly constituted of TiO₂, FeO, Fe₂O₃, SiO₂, and Al₂O₃ but with highly variable concentrations. They contain 10.63–41.42% TiO₂, 6.15–26.07% FeO, 5.86–16.75% Fe₂O₃, 7.41–61.74% SiO₂, 1.39–12.83% Al₂O₃, 0.32–4.97% CaO, 0.53–4.24% P₂O₅, 0.17–3.27% MgO, 0.15–2.97% Na₂O, 0.07–2.34% K₂O, and

Table 4 Chemical analyses of beach sand samples of Gahiramatha coast.

Sample Nos.	TiO ₂ %	Fe ₂ O ₃ %	FeO %	SiO ₂ %	Al ₂ O ₃ %	MnO %	CaO %	MgO %	V ₂ O ₅ %	K ₂ O %	Na ₂ O %	LOI %	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Cr ppm
38B	24.65	14.16	18.06	27.36	5.43	0.17	0.32	1.97	0.22	0.46	0.59	0.86	228	130	37	10	44	71
42B	31.72	11.01	16.93	28.86	4.96	0.09	0.36	1.29	0.24	0.32	0.47	0.24	1536	503	114	217	173	306
42H	33.72	12.48	24.09	18.99	3.67	0.07	0.41	1.59	0.27	0.29	0.41	0.37	1627	568	113	119	93	696
46H	31.64	12.53	18.58	26.91	2.82	0.08	0.35	1.03	0.36	0.44	0.58	0.56	1460	294	77	149	124	447
50B	28.56	12.61	19.13	21.55	7.21	0.11	1.02	2.39	0.11	0.43	0.39	0.69	1338	274	67	102	92	338
50H	32.93	13.04	22.96	17.71	2.83	0.12	1.08	2.49	0.19	0.32	0.37	0.63	1431	281	69	95	88	374
52H	29.29	13.93	31.12	16.11	2.41	0.06	0.62	0.77	0.18	0.14	0.19	0.62	674	180	81	47	106	115
53B	31.64	16.75	22.39	7.41	1.83	0.07	0.43	3.27	0.71	0.07	0.15	0.76	757	198	57	102	131	96
54B	23.38	11.67	26.07	13.28	4.02	0.12	1.43	1.82	0.63	0.14	0.22	0.33	878	265	191	78	230	55
58B	14.02	7.85	9.03	52.21	7.11	0.04	1.06	1.02	0.13	2.34	2.97	0.67	1864	119	38	183	366	145
58H	31.13	13.31	22.45	16.57	5.79	0.11	1.74	2.93	0.28	0.76	0.81	0.62	2094	305	76	69	347	423
60H	34.19	14.39	21.06	14.93	8.11	0.05	1.73	0.49	0.32	0.13	0.16	0.57	1306	242	24	93	161	207
62B	29.29	12.65	19.78	22.35	3.14	0.06	3.09	3.22	0.21	0.32	0.37	0.62	920	253	119	110	158	250
62H	30.71	12.99	21.37	17.60	4.13	0.08	3.16	3.70	0.57	0.13	0.19	0.32	1344	269	192	44	231	287
64B	41.42	12.16	23.23	12.03	1.39	0.07	0.36	0.19	0.49	0.14	0.17	0.22	1300	610	90	222	606	100
66B	34.34	13.29	17.37	26.43	2.92	0.06	0.26	0.17	0.28	0.25	0.21	0.29	568	190	27	63	109	319
66H	37.06	13.63	24.90	17.29	1.73	0.07	0.18	0.22	0.29	0.15	0.08	0.24	900	263	94	42	146	555
70H	35.93	13.22	15.53	15.15	2.07	0.06	4.46	2.83	0.79	0.21	0.17	0.69	737	297	190	42	176	74
75H	33.28	11.81	27.64	12.42	1.71	0.11	3.16	2.66	0.28	0.13	0.16	0.74	614	242	27	10	76	40
108B	12.04	5.86	8.31	57.07	6.21	0.04	3.39	2.08	0.05	1.72	2.03	0.29	781	121	80	84	123	90
112B	10.63	7.96	11.16	54.46	5.06	0.05	4.52	1.12	0.05	1.63	1.95	0.22	642	154	88	29	151	10
118B	11.03	7.19	6.15	61.74	3.19	0.03	3.29	0.37	0.05	1.36	2.77	0.16	1729	213	310	194	247	10
200B	14.61	8.49	13.48	40.07	12.83	0.09	4.97	0.48	0.13	0.79	0.96	0.49	252	108	37	76	38	27

	P ₂ O ₅ %	La ₂ O ₃ %	CeO ₂ %	Pr ₆ O ₁₁ %	Nd ₂ O ₃ %	Sm ₂ O ₃ %	Eu ₂ O ₃ ppm	Y ₂ O ₃ ppm	U ₃ O ₈ ppm	ThO ₂ %	ZrO ₂ %
38B	0.72	0.38	0.71	0.08	0.29	0.05	8	231	84	0.25	2.71
46H	0.54	0.25	0.48	0.05	0.18	0.03	4	168	54	0.17	2.07
53B	4.24	2.15	4.10	0.50	1.62	0.24	40	1110	390	1.38	0.02
54B	3.79	1.95	3.62	0.45	1.47	0.25	39	1021	423	1.24	4.47
58H	0.38	0.18	0.33	0.04	0.13	0.02	10	220	40	0.11	2.00
64B	1.49	0.74	1.40	0.15	0.55	0.09	10	490	150	0.45	3.60
66B	0.53	0.19	0.36	0.04	0.14	0.02	5	150	46	0.12	2.12
70H	1.59	0.78	1.46	0.18	0.59	0.10	10	450	150	0.51	3.00
75H	1.06	0.54	1.00	0.12	0.39	0.07	8	284	98	0.36	2.61

B= Bulk; H= Bromoform heavy fraction; 38-75= Ekakula, 108-112= Ekakulanasi, 118= Babubali, 200= Ekakula river side

0.05-0.71% V₂O₅. Trace amounts of Pb, Zn, Cu, Ni, Co, and Cr are also recorded in these samples. By heavy media separation increase in TiO₂, FeO, Fe₂O₃, CaO, MgO, V₂O₅, Pb, Zn, Cr, and decrease in SiO₂, Al₂O₃, Na₂O, K₂O have been observed. FeO>Fe₂O₃ is the characteristic of both the bulk as well as heavy fractions. All the samples contain appreciable amounts of La, Ce, Pr, Nd, Sm, Eu, Y, U, Th, and Zr (Table 4).

Correlation coefficients of various elements in the above samples are given in Table 5a which demonstrate that TiO₂ is positively correlated with FeO, Fe₂O₃, V₂O₅, Zn, and Cr and negatively correlated with SiO₂, Al₂O₃, Na₂O, K₂O, and CaO. Fe₂O₃ has significant positive relationship with FeO, MnO, V₂O₅ and with Cr indicating their close association. Both FeO and Fe₂O₃ are positively correlated with MnO, V₂O₅, and Cr; and negatively correlated with SiO₂, Na₂O, and K₂O. Na₂O, K₂O, and Al₂O₃ have positive correlation, while V₂O₅, MnO, and Zn have negative correlation, with SiO₂. Positive correlations exist between Pb and Co, Ni, Zn; and

between Ni and Co.

The correlation coefficients of the REE, radioactive elements, and P₂O₅ of nine samples are given in Table 5. It is interesting to find that La₂O₃, CeO₂, Pr₆O₁₁, Nd₂O₃, Sm₂O₃, Eu₂O₃, Y₂O₃, U₃O₈, ThO₂, and P₂O₅ have very strong positive correlation among themselves indicating the occurrence of REE-phosphates such as monazite. They all have negative correlation with ZrO₂.

5. R-mode Factor Analysis of Chemical Data

Major, minor and trace elements data of beach sand samples of Gahiramatha coast were analysed using multivariate factor model of correlation matrix (factor model of Davis, 1973). This has been done after standardisation which allowed retention of common factors by minima or inflection points of eigen values (Sahu, 1982). The inflection point method yielded three common factors (Table 6a) which were varimax rotated to get geochemical inferences.

Table 5 Normalised correlation coefficients among chemical components in beach sand samples of Gahiramatha coast.

(a) n = 23																		
	TiO ₂	Fe ₂ O ₃	FeO	SiO ₂	Al ₂ O ₃	MnO	CaO	MgO	V ₂ O ₅	K ₂ O	Na ₂ O	LOI	Pb	Zn	Cu	Ni	Co	Cr
Cr	0.68	0.54	0.50	-0.43	-0.09	0.27	-0.56	0.09	0.40	-0.32	-0.41	0.22	0.44	0.48	-0.11	0.25	0.06	1.00
Co	0.07	-0.09	-0.11	-0.04	-0.24	-0.39	0.01	-0.14	0.19	0.02	0.05	-0.39	0.69	0.40	0.43	0.50	1.00	
Ni	-0.04	-0.21	-0.27	0.16	0.10	-0.41	-0.16	-0.25	-0.06	0.17	0.24	-0.32	0.66	0.36	0.30	1.00		
Cu	-0.10	-0.16	-0.15	0.08	-0.26	-0.20	0.20	0.18	0.04	0.02	0.08	-0.48	0.38	0.39	1.00			
Zn	0.69	0.43	0.48	-0.52	-0.45	0.20	-0.35	-0.01	0.49	-0.47	-0.46	-0.23	0.58	1.00				
Pb	0.17	-0.02	-0.03	-0.04	-0.09	-0.27	-0.08	0.07	0.04	0.07	0.11	-0.21	1.00					
LOI	0.27	0.47	0.35	-0.40	0.10	0.44	0.04	0.55	0.29	-0.18	-0.18	1.00						
Na ₂ O	-0.86	-0.82	-0.83	0.89	0.57	-0.37	0.38	0.05	-0.78	0.96	1.00							
K ₂ O	-0.81	-0.82	-0.83	0.91	0.58	-0.36	0.35	-0.02	-0.81	1.00								
V ₂ O ₅	0.79	0.77	0.68	-0.85	-0.46	0.41	-0.33	0.15	1.00									
MgO	0.01	0.14	0.14	-0.21	0.10	0.37	0.38	1.00										
CaO	-0.53	-0.50	-0.41	0.33	0.36	-0.25	1.00											
MnO	0.45	0.53	0.62	-0.52	0.01	1.00												
Al ₂ O ₃	-0.54	-0.42	-0.42	0.52	1.00													
SiO ₂	-0.87	-0.88	-0.90	1.00														
FeO	0.82	0.83	1.00															
Fe ₂ O ₃	0.87	1.00																
TiO ₂	1.00																	

(b) n = 9											
	P ₂ O ₅	La ₂ O ₃	CeO ₂	Pr ₆ O ₁₁	Nd ₂ O ₃	Sm ₂ O ₃	Eu ₂ O ₃	Y ₂ O ₃	U ₃ O ₈	ThO ₂	ZrO ₂
ZrO ₂	-0.44	-0.42	-0.43	-0.43	-0.42	-0.37	-0.50	-0.44	-0.39	-0.42	1.00
ThO ₂	0.99	1.00	1.00	1.00	1.00	1.00	0.86	0.96	0.99	1.00	
U ₃ O ₈	0.99	1.00	1.00	0.99	1.00	0.99	0.89	0.97	1.00		
Y ₂ O ₃	0.97	0.97	0.97	0.97	0.97	0.96	0.94	1.00			
Eu ₂ O ₃	0.87	0.87	0.87	0.89	0.87	0.85	1.00				
Sm ₂ O ₃	0.98	1.00	1.00	1.00	1.00	1.00					
Nd ₂ O ₃	0.99	1.00	1.00	1.00	1.00						
Pr ₆ O ₁₁	0.99	1.00	1.00	1.00							
CeO ₂	0.99	1.00	1.00								
La ₂ O ₃	0.99	1.00									
P ₂ O ₅	1.00										

The factor-1 explains 42.36% of the total variances and is strongly loaded positively in TiO₂, FeO, Fe₂O₃, V₂O₅, Cr, and Zn; and negatively in SiO₂, Al₂O₃, CaO, Na₂O, and K₂O. This factor can be correlated with ilmenite, hematite, garnet, quartz, orthoclase, microcline which were transported, sorted and deposited on the beach.

The factor-2 explains 19.77% of the total variances and is loaded with trace metals like Pb, Zn, Cu, Ni, and Co. The factor-3 explains only 9.62% of the total variances and may be correlated with garnet, anthophyllite, and hornblende.

P₂O₅, La₂O₃, CeO₂, Pr₆O₁₁, Nd₂O₃, Sm₂O₃, Eu₂O₃, Y₂O₃, U₃O₈, ThO₂, and ZrO₂ in nine samples were processed separately which yielded two factors explaining 97.66% of the variances (Table 6b). The factor-1 explains 90.16% of the total variances and is strongly loaded positively with P₂O₅, La₂O₃, CeO₂, Pr₆O₁₁, Nd₂O₃, Sm₂O₃, Eu₂O₃, Y₂O₃, U₃O₈, and ThO₂ and can be correlated with the mineral monazite. Factor-2 explains 7.50% of the total variances, loaded positively

with ZrO₂ and is attributed by zircon.

6. Monazite-Zircon Preconcentrates

Five samples (sample Nos. 38, 46, 54, 66, and 75) have been separated into magnetic and non-magnetic fractions with the help of hand magnet and iso-dynamic separator (0.6 Amp current with a side tilt of 20° and forward slope of 30°). Monazite, zircon, quartz, and feldspar were predominantly contained together with minor amounts of sillimanite, garnet, anthophyllite and diopside in the non-magnetic fraction of the isodynamic separator. This non-magnetic fraction was further subjected to heavy media separation using bromoform to remove quartz and feldspar. The bromoform heavy fraction thus constituted of dominantly monazite and zircon (Fig. 5). These monazite-zircon preconcentrate samples are enriched to a great extent in their rare earth and radioactive elements. They contain 1.66–9.02% La₂O₃, 3.11–16.80% CeO₂, 0.37–2.08% Pr₆O₁₁, 1.21–6.83% Nd₂O₃, 0.20–1.16% Sm₂O₃, 0.003–0.018% Eu₂O₃, 0.121–0.473% Y₂O₃, 14.9–27.8% ZrO₂, 1.02–5.74% ThO₂, 0.039–0.196% U₃O₈, and 3.90–17.56% P₂O₅ (Table 7).

Table 6 Rotated factor matrix of beach sand samples of Gahiramatha coast.

(a) n = 23					(b) n = 9			
	Factor-1	Factor-2	Factor-3	Communality		Factor-1	Factor-2	Communality
TiO ₂	0.96	0.09	0.08	0.93	P ₂ O ₅	0.96	-0.24	0.99
Fe ₂ O ₃	0.91	-0.13	0.21	0.88	La ₂ O ₃	0.97	-0.22	1.00
FeO	0.89	-0.14	0.20	0.85	CeO ₂	0.97	-0.22	1.00
SiO ₂	-0.93	0.03	-0.23	0.92	Pr ₆ O ₁₁	0.97	-0.23	1.00
Al ₂ O ₃	-0.61	-0.14	0.33	0.50	Nd ₂ O ₃	0.97	-0.21	1.00
MnO	0.48	-0.35	0.49	0.59	Sm ₂ O ₃	0.98	-0.16	0.99
CaO	-0.57	-0.01	0.36	0.46	Eu ₂ O ₃	0.84	-0.37	0.84
MgO	-0.01	0.05	0.91	0.83	Y ₂ O ₃	0.95	-0.27	0.96
V ₂ O ₅	0.84	0.08	0.16	0.74	U ₃ O ₈	0.98	-0.19	1.00
K ₂ O	-0.91	0.10	0.03	0.85	ThO ₂	0.97	-0.22	0.99
Na ₂ O	-0.93	0.14	0.07	0.89	ZrO ₂	-0.21	0.97	0.99
LOI	0.23	-0.40	0.72	0.72	Eigen values	9.92	0.83	
Pb	0.06	0.91	0.10	0.84	% of trace	90.16	7.50	
Zn	0.62	0.62	-0.03	0.77	Cumulative % trace	90.16	97.66	
Cu	-0.07	0.64	-0.02	0.41				
Ni	-0.11	0.75	-0.19	0.62				
Co	0.04	0.79	-0.20	0.66				
Cr	0.56	0.31	0.22	0.46				
Eigen values	7.63	3.56	1.73					
% of trace	42.36	19.77	9.62					
Cumulative % trace	42.36	62.13	71.75					

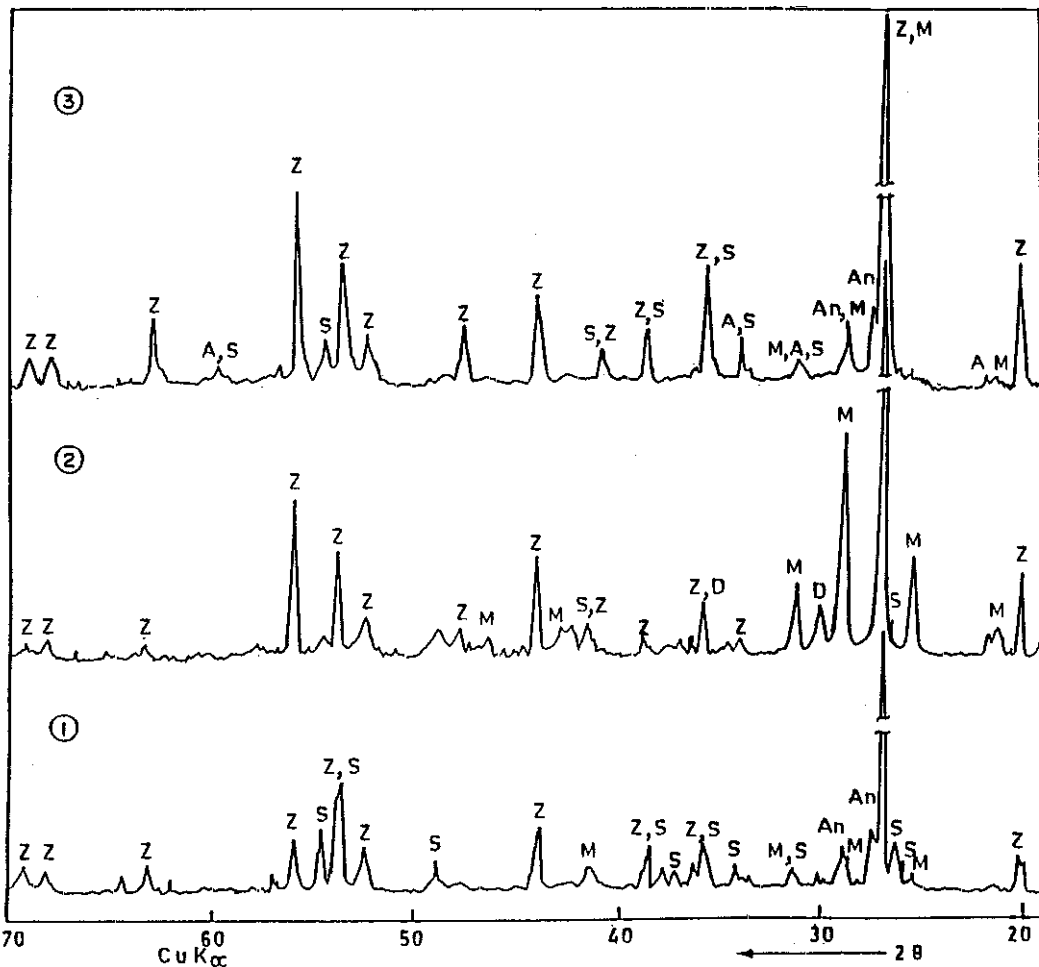


Fig. 5 X-ray diffraction patterns of monazite-zircon preconcentrate samples of Gahiramatha coast. M= monazite; Z= zircon; S=sillimanite; A=almandine, An=anthophyllite; D=diopside. Location: 1=Ekakula No 38, 2=Ekakula No 53, 3=Ekakula No 64

Table 7 Chemical analyses of monazite-zircon pre-concentrate samples (wt %).

Sample Nos	38	46	53	66	75
Yield %	9.76	12.50	21.59	11.71	9.68
ZrO ₂	27.80	14.90	20.70	18.10	26.00
ThO ₂	2.61	1.23	5.74	1.02	3.54
P ₂ O ₅	7.22	3.90	17.56	4.31	10.34
La ₂ O ₃	3.94	1.83	9.02	1.66	5.35
CeO ₂	7.28	3.44	16.80	3.11	9.90
Pr ₆ O ₁₁	0.86	0.40	2.08	0.37	1.23
Nd ₂ O ₃	2.94	1.36	6.83	1.21	3.93
Sm ₂ O ₃	0.51	0.20	1.16	0.21	0.67
Eu ₂ O ₃	0.008	0.003	0.018	0.004	0.008
Y ₂ O ₃	0.237	0.121	0.473	0.128	0.283
U ₃ O ₈	0.086	0.039	0.196	0.039	0.098

7. Discussion and Conclusion

The heavy mineral assemblage consisting of ilmenite, hematite, garnet, monazite, zircon, rutile, magnetite, sillimanite, pyroxene, and amphibole is found in the beach sands between Hansua and Dhamra rivers, being concentrated in the Ekakula beach. The contents of the heavy minerals vary from 26.37 to as high as 100%. The rivers Brahmani and Baitarani join together to form Dhamra before meeting the Bay of Bengal (Fig. 1). The catchment area of Baitarani is dominantly granitic terrain whereas the catchment area of river Brahmani is dominantly Eastern Ghats granulites. The Eastern Ghats rocks (khondalite, charnockite, calc-silicate granulite, leptynite, migmatite, gneiss, and basic granulite, and pegmatite) contain ilmenite, monazite, and zircon among others as minor accessories. The Eastern Ghats provenance appears to be the major source for the heavy mineral assemblages of the Ekakula beach, like that of the Chhatrapur placer deposit (Bhattacharya and Sengupta, 1994). The possibilities of some of the heavy minerals influx from the catchment areas of river Baitarani cannot be ruled out. The placer minerals together with other detrital minerals have been subjected to mechanical processing. Tidal waves, littoral drifts, fluctuation of the sea level and wind action have played their role in the concentration of heavy minerals. The current pattern around Ekakula is very interesting being more or less circular in nature. As a result, the heavy minerals do not travel over a long distance along the shore and are reworked and mechanically concentrated around Ekakula. The well rounded and sorted grains may indicate their long distance travel under fluvial environment and/or reworked for a long time under marine conditions. The sediments were probably subjected to a high energy surf zone as indicated by the conchoidal to subconchoidal fractures in garnet which were developed by wave

induced collision.

Ilmenite, monazite, and zircon are the economic placer minerals having modal percentages of 70.42, 5.73, and 2.52 respectively. The monazite and zircon concentration at Ekakula is higher than other placer deposits of east coast of India. The bulk samples contain 10.63–41.42% TiO₂, 6.15–26.07% FeO, 5.86–16.75% Fe₂O₃, 7.41–61.74% SiO₂, 1.39–12.83% Al₂O₃, 0.32–4.97% CaO, 0.53–4.24% P₂O₅, 0.17–3.27% MgO, 0.15–2.97% Na₂O, 0.07–2.34% K₂O, and 0.05–0.71% V₂O₅ together with appreciable amounts of La, Ce, Pr, Nd, Sm, Eu, Y, U, Th, Zr, and trace amounts of Pb, Zn, Cu, Ni, Co, and Cr. The grain size of ilmenite, monazite, and zircon are mostly in between 100 and 300 µm having mean feret diameter of 194 µm, 173 µm, and 183 µm respectively; and they are well rounded in shape. The silicate gangue minerals are slightly coarser in size (113 to 611 µm with a mean feret diameter of 238 µm). The above indicates that by a simple size classification most of the ilmenite, monazite, and zircon can be obtained in a size range of 300–100 µm. They may be processed to obtain their individual concentrates by adopting gravity and magnetic methods.

The electron microprobe analyses indicate that the TiO₂, and FeO (total iron) content in ilmenite varies from 50.02 to 54.73% and 42.42–46.90% respectively with a small amounts of Al₂O₃, MnO, MgO, CaO, BaO, SiO₂, V₂O₃, Cr₂O₃, and ZnO. The Al₂O₃, MgO, MnO, V₂O₃, and BaO are relatively more in the ilmenite than the intergrown hematite. The iron content in the ilmenite concentrate is likely to be increased due to the presence of exsolved hematite in some of the ilmenite grains. The hematite lamellae in ilmenite and ilmenite lamellae in hematite indicate that they are exsolved from the FeTiO₃-Fe₂O₃ solid solution. The two generations of ilmenite laths may indicate their crystallisation at different periods of temperature. The coarser first generation lamellae might have formed at temperatures between 530–600°C while the finer second generation lamellae may represent later stages of crystallisation in the range of 450–500°C (Ahmed et al., 1992). It may be mentioned here that the temperature-pressure conditions of metamorphism of the Eastern Ghats granulites in north Orissa are >650°C and 6 kb (Park and Dash, 1984).

It may be worth reporting that the monazite-zircon pre-concentrates have considerably high amounts of La, Ce, Pr, Nd, Sm, Eu and Y in addition to 14.9–27.8% ZrO₂, 1.02–5.74% ThO₂, and 0.04–0.20% U₃O₈. This heavy mineral placer deposit has a good economic potential for the above radioactive and rare earth elements besides titanium.

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