Chapter 12
Mineral Chemistry of Ilmenites as a Source Indicator for Coastal Sediments Between Vamsadhara and Nagavali River Mouth, North Coastal, Andhra Pradesh

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Abstract Ilmenites come from coastal sediments between the mouths of the Vamsadhara and Nagavali rivers, north coastal Andhra Pradesh, was studied using ilmenite end-member components. Ilmenite mineral chemistry has been studied from various environments to understand provenance by electron microprobe analyzer (EPMA). This study reveals that the ilmenite with the end-member components of Fe-Ti oxides is mainly ilmenite and has minor proportions of hematite, geikielite, and pyrophanite. The end-member compositions of Fe-Ti oxides and manganese/magnesium ratio indicate all the ilmenites of beach, dune, and estuarine environments are from the pyroxene granulites, khondalites, basic charnockites, and migmatites. Ilmenites are ferrian types and Ti/ (Ti + Fe) ratio is <0.5 indicating these are recently contributed to placer deposits. Ilmenites are mainly concentrated in fine fraction (+230) 51.50%. Ilmenite contains average TiO_2 content is 52% with a low concentration of trace elements.

Keywords Ilmenite · Mineral chemistry · Provenance · Charnockite · Khondalite · EPMA

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12.1 Introduction

Ilmenite ($FeTiO_3$) is a titanium-rich ore mineral. It has a solid solution with pyrophanite ($MgTiO_3$), geikielite ($MnTiO_3$), and hematite (Fe_2O_3). Generally, under microscope, ilmenite exhibits a significant amount of intergrowths with other Ti-Fe oxides due to exsolutions, hydrothermal, or oxidation processes. There are also trace amounts of Si, Al, Ca, Cr, Cu, and Zn in ilmenites. The mineral chemical characteristics of ilmenite are very useful to understand the provenance of ilmenite-bearing coastal sediments and also helpful in the selection of adaption methods of beneficiation for better recovery and extraction process.

Ilmenite geochemistry is most important for the selection of processing methodology either the chlorite route or sulfite route to produce titanium dioxide (TiO_2). The mineral end-member compositions of ilmenite are essential for ore dressing and mineral beneficiation processes. Ilmenite‘s economic value can be determined by how altered or weathered it is. Ilmenite deposits in India have not received much attention in terms of mineral chemistry studies, and the coastal placer deposit at Nagavali-Vamsadhara (the subject of the current study) in particular. Rao and Sengupta (2014), Laxmi et al. (2014), Mohapatra et al. (2015), Acharya et al. (2015), and Ganapati Rao et al. (2019) are a few studies that looked at the ilmenite geochemistry of India‘s east coast.

12.2 Study Area and Regional Geology

The study area is a coastal stretch that extends to 33 km from the Nagavali to the Vamsadhara river mouths, Srikakulam district, North coastal Andhra Pradesh, India (Fig.12.1). The geographical coordinates of the study area are between 18°12.410′N and 18°21.995′N latitude, between 83°55.432′E and 84°08.730′E longitude. The examined coastal region is a portion of a sedimentary basin next to the Granulite Belt of the Eastern Ghats in the middle (EGGB). The three main types of rocks are as follows: (i) charnockite group of rocks; (ii) basic granulites formed from tholeiitic magma; and (iii) khondalite group of rocks (Ramam and Murthy 1997; Yugandhara Rao et al. 2001). The general trend of the rock formation is NW-SE following the major lineament trend (Fig. 12.2).

12.3 Methodology

12.3.1 Sample Collection and Preparation

In the research region, 38 sediment samples from coastal sediment were collected over 17 traverses parallel to the coast, with 2 km between traverses (Fig. 12.1). A polyvinyl chloride pipe with a 3-inch diameter and 30-cm length was used at each

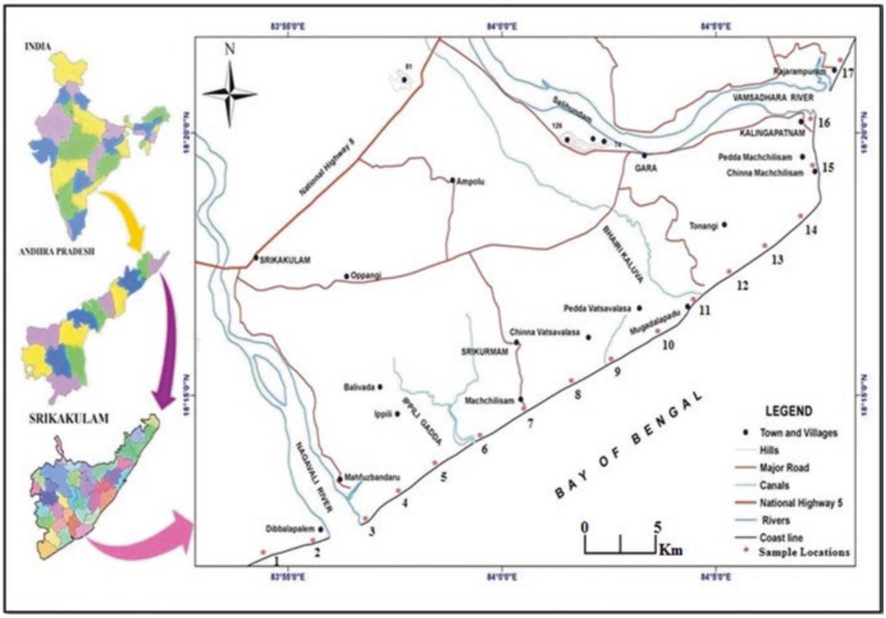

Fig. 12.1 The study area and sample location map

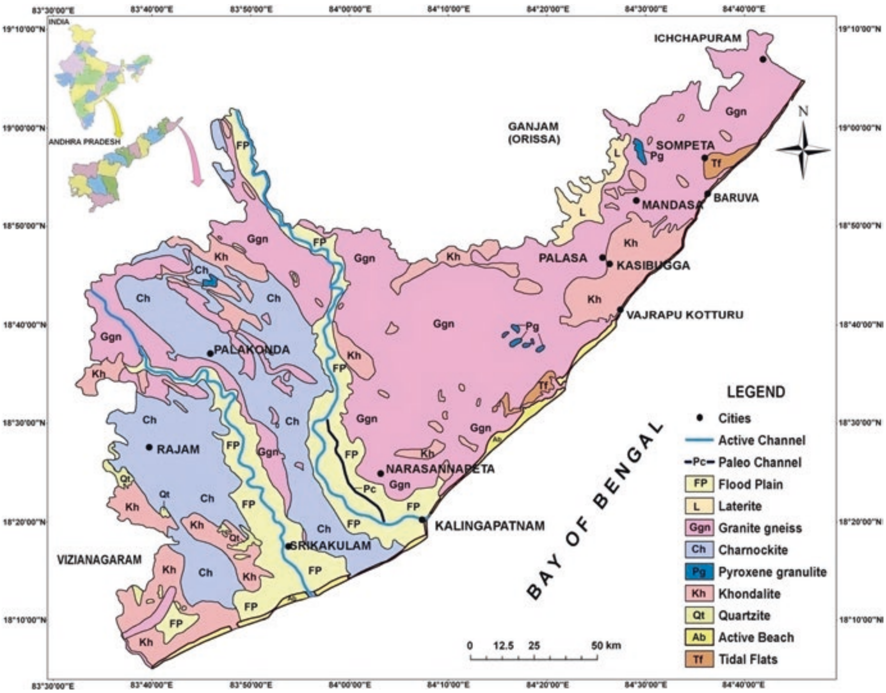

Fig. 12.2 Map of the Geology of Srikakulam district

station to collect sediment samples, penetrating the sediment layers to a depth of 10 cm. By using the coning and quartering procedure, the sediment samples were decreased, and a representative amount was taken for sediment treatment to separate the heavy minerals. A total of 38 ilmenite grains were selected for mineral chemistry analysis after being differentiated from other grains in each sample using a binocular petrological microscope.

Every sample's chosen ilmenite mineral grains were put on an epoxy resin slide of standard size for additional coating, polishing, and grinding to make sure the top and bottom of the resin blocks were parallel to one another. Using a fine silicon carbide abrasive, lapping is used to create a smooth surface (class 600). Samples were polished using very fine alumina slurry with a size range of 6–0.30 microns and fine silicon carbide (SiC) paper. To get rid of polishing grit and other surface impurities, polished samples are subsequently rinsed in clean water in an ultrasonic cleaner. After that, the sample was cleaned using a fan and allowed to air dry. To obtain good electron conductivity and interaction, the samples are coated with a coating of carbon.

An electron probe microanalyzer (EPMA) was used to analyze the mineral grains of ilmenite (CAMECA SX-100). An electron beam with a 15 kV acceleration voltage and a 20 nA beam current stimulated the polished surfaces of 38 ilmenite granules. We maintained a ~1 µm beam radius. Most of the element calibrations were performed using natural mineral standards (almandine-Fe: rhodonite-Mn; TiO_2-Ti; diopside-Mg, Ca; albite-Na, Al; chromite-Cr; hematite-Fe; wollastonite-Ca; corundum-Al; and orthoclase for Si and K).

12.4 Results

The detailed geochemical data of ilmenites from beach, dune, and estuarine environments were given in Tables 12.1, 12.2, and 12.3, respectively. The structure of ilmenites has been calculated based on two cations, three oxygens, and end members are also given in the respective tables. The ratios of manganese/magnesium and Ti/(Ti + Fe) of ilmenites were given in Table 12.4. The end-member compositions of beach sediments' Fe-Ti oxides show that the proportions of ilmenite, pyrophanite, geikielite, and hematite range from 83.26% to 98.53%, 0.29% to 1.25%, 0.20% to 4.94%, and 0.25% to 11.41%, respectively (Table 12.1).

Ilmenite component in a dune environment ranges from 83.78% to 97.67%, pyrophanite from 0.22% to 4.21%, geikielite from 0.23% to 5.90%, and hematite from 0.59% to 9.91%, according to the end-member composition (Table 12.2). The end-member composition of estuarine environments shows that ilmenite varies from 91.17% to 96.89%, pyrophanite varies from 0.31% to 5.77%, geikielite varies from 1.55% to 7.02%, and hematite varies from 0.69% to 2.52%, with eskolaite being negligible in all environments (Table 12.3).

Ilmenites originating from several groups of rocks are distinguished using a rhombohedral quaternary system (Haggerty 1976; Nayak and Mohapatra 1998; Nayak et al.

Table 12.1 Chemical composition of ilmenites of coastal sediment from beach environment between Vamsadhara and Nagavali river mouths

Traverse no.	4		8		14		30		32				
Grain no.	1	2	3	4	5	6	7	8	9	10	Min.	Max.	Avg.
SiO_2	0.030	0.020	0.000	0.050	0.070	0.070	0.020	0.010	0.080	0.030	0.080	0.080	0.040
TiO_2	52.640	45.940	52.140	52.370	53.020	50.190	51.300	52.880	51.840	52.420	53.020	53.020	51.470
Al_2O_3	0.000	0.040	0.010	0.020	0.000	0.050	0.060	0.000	0.000	0.000	0.060	0.060	0.020
Cr_2O_3	0.020	0.230	0.150	0.030	0.030	0.090	0.070	0.070	0.000	0.080	0.230	0.230	0.080
FeO	46.620	49.410	44.610	45.620	44.210	46.300	46.170	44.810	45.480	46.010	49.410	49.410	45.920
MnO	0.590	0.320	0.520	0.190	0.140	0.360	0.250	0.170	0.190	0.340	0.590	0.590	0.310
MgO	0.110	1.090	1.130	0.980	1.310	0.940	0.050	1.320	0.320	0.290	1.320	1.320	0.750
CaO	0.050	0.000	0.010	0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.060	0.060	0.010
Na_2O	0.030	0.000	0.000	0.010	0.030	0.010	0.000	0.000	0.000	0.010	0.030	0.030	0.010
K_2O	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.020	0.020	0.000
	100	97.05	98.57	99.33	98.80	98.01	97.91	99.27	97.91	99.18	100	100	99
On the basis of three oxygen													
Si	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	1.000	0.890	1.000	0.990	1.010	0.960	0.990	1.000	1.000	1.000	1.010	1.010	0.980
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.980	1.060	0.950	0.960	0.940	0.990	0.990	0.940	0.980	0.980	1.060	1.060	0.980
Mn	0.010	0.010	0.010	0.000	0.000	0.010	0.010	0.000	0.000	0.010	0.010	0.010	0.010
Mg	0.000	0.040	0.040	0.040	0.050	0.040	0.000	0.050	0.010	0.010	0.050	0.050	0.030
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

(continued)

Table 12.1 (continued)

Traverse no.	4		8		14		30		32				
Grain no.	1	2	3	4	5	6	7	8	9	10	Min.	Max.	Avg.
End-member compositions													
Geikielite	0.400	4.150	4.260	3.680	4.930	3.580	0.200	4.940	1.220	1.090	4.940	4.940	2.850
Pyrophanite	1.250	0.700	1.110	0.400	0.290	0.770	0.550	0.360	0.410	0.740	1.250	1.250	0.660
Eskolaite	0.040	0.470	0.300	0.050	0.050	0.190	0.140	0.130	0.000	0.160	0.470	0.470	0.150
Ilmenite	98.070	83.260	93.900	95.180	95.620	91.780	98.530	94.570	98.370	98.010	98.530	98.530	94.730
Hematite	0.250	11.410	0.440	0.690	0.000	3.680	0.580	0.000	0.000	0.000	11.410	11.410	1.710
	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 12.2 Chemical composition of ilmenites from coastal sediment of dune environment between Vamsadhara and Nagavali river mouths

Traverse no.	3		4		6		8		14		26		28		32				
Grain no.	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Min.	Max.	Avg.
SiO_2	0.020	0.030	0.010	0.050	0.040	0.020	0.030	0.000	0.180	0.150	0.180	0.080	0.010	0.050	0.040	0.000	0.000	0.180	0.060
TiO_2	51.330	47.070	51.980	52.130	50.740	50.890	51.810	50.850	58.620	48.930	56.670	51.180	53.310	49.720	52.140	52.300	47.070	58.620	51.850
Al_2O_3	0.010	0.040	0.000	0.000	0.020	0.000	0.030	0.020	0.080	0.070	0.240	0.070	0.000	0.030	0.000	0.000	0.000	0.240	0.040
Cr_2O_3	0.000	0.100	0.090	0.100	0.000	0.030	0.130	0.000	0.030	0.010	0.050	0.000	0.000	0.040	0.020	0.030	0.000	0.130	0.040
FeO	45.170	48.580	45.590	45.470	47.190	46.110	44.120	45.930	32.970	46.600	33.340	45.150	43.000	46.720	45.650	44.090	32.970	48.580	44.110
MnO	0.130	0.100	0.550	0.580	0.750	0.200	0.510	0.240	0.870	0.550	1.810	0.460	0.270	0.250	0.250	0.150	0.100	1.810	0.480
MgO	1.200	1.560	0.630	0.690	0.100	0.470	1.550	0.670	0.060	0.810	0.110	0.490	1.450	0.810	0.830	1.440	0.060	1.560	0.800
CaO	0.020	0.000	0.000	0.020	0.020	0.000	0.010	0.010	0.050	0.000	0.010	0.050	0.000	0.010	0.000	0.000	0.000	0.050	0.010
Na_2O	0.010	0.010	0.000	0.000	0.030	0.000	0.020	0.000	0.010	0.000	0.020	0.010	0.020	0.000	0.000	0.000	0.000	0.030	0.010
K_2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.010	0.000	0.020	0.000
	97.880	97.480	98.840	99.040	98.880	97.730	98.200	97.720	92.850	97.140	92.420	97.490	98.070	97.610	98.940	98.020	92.420	99.040	97.390
On the basis of three oxygens																			
Si	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.990	0.900	0.990	0.990	0.970	0.980	0.990	0.980	1.210	0.950	1.170	0.990	1.020	0.960	0.990	1.000	0.900	1.210	1.010
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.960	1.030	0.970	0.960	1.000	0.990	0.940	0.990	0.760	1.000	0.770	0.970	0.920	1.000	0.970	0.940	0.760	1.030	0.950
Mn	0.000	0.000	0.010	0.010	0.020	0.000	0.010	0.010	0.020	0.010	0.040	0.010	0.010	0.010	0.010	0.000	0.000	0.040	0.010
Mg	0.050	0.060	0.020	0.030	0.000	0.020	0.060	0.030	0.000	0.030	0.000	0.020	0.050	0.030	0.030	0.050	0.000	0.060	0.030
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

(continued)

Table 12.2 (continued)

Traverse no.	3		4		6		8		14		26		28		32				
Grain no.	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Min.	Max.	Avg.
End-member compositions																			
Geikielite	4.550	5.900	2.380	2.590	0.390	1.810	5.860	2.550	0.230	3.120	0.440	1.870	5.490	3.090	3.140	5.460	0.230	5.900	3.050
Pyrophanite	0.290	0.220	1.180	1.250	1.620	0.420	1.090	0.520	2.030	1.210	4.210	1.010	0.580	0.530	0.540	0.330	0.220	4.210	1.060
Eskolaite	0.010	0.190	0.170	0.210	0.000	0.060	0.270	0.000	0.070	0.020	0.110	0.000	0.000	0.070	0.040	0.050	0.000	0.270	0.080
Ilmenite	93.730	83.780	95.620	95.340	95.170	96.160	91.660	95.140	97.670	90.380	95.250	96.310	93.930	92.200	95.690	94.160	83.780	97.670	93.890
Hematite	1.430	9.910	0.650	0.610	2.830	1.540	1.110	1.790	0.000	5.270	0.000	0.800	0.000	4.110	0.590	0.000	0.000	9.910	1.920
	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 12.3 Chemical composition of ilmenites from estuarine sediment of Vamsadhara and Nagavali rivers

Traverse no.	NR 1		NR 2		NR 3		VR 1		VR 2		VR 3				
Grain no.	27	28	29	30	31	32	33	34	35	36	37	38	Min.	Max.	Avg.
SiO_2	0.030	0.050	0.030	0.060	0.030	0.050	0.050	0.020	0.060	0.000	0.000	0.060	0.000	0.060	0.040
TiO_2	52.620	51.600	52.750	52.520	52.300	52.270	53.560	51.310	52.110	52.980	51.830	53.850	51.310	53.850	52.480
Al_2O_3	0.010	0.000	0.030	0.000	0.020	0.020	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.040	0.010
Cr_2O_3	0.020	0.030	0.040	0.070	0.120	0.030	0.000	0.080	0.070	0.060	0.040	0.250	0.000	0.250	0.070
FeO	44.720	46.040	43.810	45.950	46.050	46.840	44.930	47.360	46.400	43.330	45.880	43.760	43.330	47.360	45.420
MnO	0.160	0.280	0.500	0.670	0.320	0.220	0.150	0.290	0.620	2.720	0.260	0.290	0.150	2.720	0.540
MgO	0.840	0.410	1.280	0.650	0.950	0.490	1.550	0.440	0.780	0.780	0.660	1.900	0.410	1.900	0.890
CaO	0.000	0.080	0.030	0.000	0.010	0.010	0.010	0.000	0.000	0.000	0.000	0.040	0.000	0.080	0.020
Na_2O	0.020	0.020	0.000	0.000	0.010	0.000	0.020	0.010	0.030	0.000	0.000	0.030	0.000	0.030	0.010
K_2O	0.020	0.010	0.020	0.000	0.010	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.020	0.010
	98.44	98.51	98.48	99.91	99.82	99.93	100	99.51	100	99.92	98.68	100	98	100	99
On the basis of three oxygens															
Si	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	1.010	0.990	1.010	0.990	0.990	0.990	1.000	0.970	0.980	1.000	0.990	1.010	0.970	1.010	0.990
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.950	0.980	0.930	0.970	0.970	0.990	0.930	1.000	0.970	0.910	0.980	0.910	0.910	1.000	0.960
Mn	0.000	0.010	0.010	0.010	0.010	0.000	0.000	0.010	0.010	0.060	0.010	0.010	0.000	0.060	0.010
Mg	0.030	0.020	0.050	0.020	0.040	0.020	0.060	0.020	0.030	0.030	0.030	0.070	0.020	0.070	0.040
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

(continued)

Table 12.3 (continued)

Traverse no.	NR 1		NR 2		NR 3		VR 1		VR 2		VR 3				
Grain no.	27	28	29	30	31	32	33	34	35	36	37	38	Min.	Max.	Avg.
End-member compositions															
Geikielite	3.200	1.550	4.830	2.420	3.570	1.840	5.740	1.660	2.910	2.930	2.510	7.020	1.550	7.020	3.350
Pyrophanite	0.350	0.600	1.060	1.420	0.690	0.470	0.310	0.610	1.320	5.770	0.570	0.600	0.310	5.770	1.150
Eskolaite	0.050	0.060	0.090	0.130	0.230	0.060	0.010	0.170	0.150	0.120	0.090	0.490	0.010	0.490	0.140
Ilmenite	96.410	96.890	94.020	95.340	94.210	96.520	93.940	95.040	93.770	91.170	96.040	91.880	91.170	96.890	94.600
Hematite	0.000	0.910	0.000	0.690	1.310	1.100	0.000	2.520	1.850	0.000	0.800	0.000	0.000	2.520	0.770
	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 12.4 Ratios of Mn/Mg and Ti/(Ti + Fe) of ilmenite from sediments between Vamsadhara and Nagavali river mouths

Traverse no.	Grain no.	Mn/Mg	Ti/(Ti + Fe)
Beach environment			
4	1	7.100	0.470
	2	0.380	0.420
8	3	0.590	0.470
	4	0.250	0.470
14	5	0.130	0.480
	6	0.490	0.460
30	7	6.250	0.460
	8	0.160	0.480
32	9	0.770	0.470
	10	1.520	0.470
	Min.	0.130	0.420
	Max.	7.100	0.480
	Avg.	1.650	0.460
Dune environment			
3	11	0.140	0.470
	12	0.080	0.430
4	13	1.120	0.470
	14	1.090	0.470
6	15	9.350	0.450
	16	0.530	0.460
8	17	0.420	0.480
	18	0.460	0.460
14	19	20.040	0.580
	20	0.870	0.450
26	21	21.690	0.570
	22	1.220	0.470
28	23	0.240	0.490
	24	0.390	0.450
32	25	0.390	0.470
	26	0.140	0.480
	Min.	0.080	0.430
	Max.	21.690	0.580
	Avg.	3.640	0.480
Estuarine environment			
NR 1	27	0.240	0.480
	28	0.870	0.460
NR 2	29	0.500	0.480
	30	1.330	0.470
NR 3	31	0.430	0.470
	32	0.580	0.460

(continued)

Table 12.4 (continued)

Traverse no.	Grain no.	Mn/Mg	Ti/(Ti + Fe)
VR 1	33	0.120	0.480
	34	0.830	0.460
VR 2	35	1.020	0.460
	36	4.450	0.490
VR 3	37	0.510	0.470
	38	0.190	0.490
	Min.	0.120	0.460
	Max.	4.450	0.490
	Avg.	0.920	0.470

2012) (Fig. 12.3). The five fields in this picture are as follows: (1) parametamorphites (Mn-rich); (2) intrusive (pegmatites and carbonatites); (3) basic suits (amphibolites and granite gneisses); (4) intrusive acid and anorthosite suites; and (5) kimberlites. All ilmenites fall in field 3 of the basic suite of rocks, which is the ilmenite field. The end-member compositions of Fe-Ti oxides from beach, dune, and estuarine environments were plotted in the rhombohedral quarternary ($FeTiO_3$-$MnTiO_3$-$MgTiO_3$-Fe_2O_3) diagrams (Haggerty 1976; Nayak and Mohapatra 1998).

Ilmenites formed from beach sediment had an average TiO_2 content of 52.48%, ranging from 51.31% to 53.85% for dune sediments, 47.07% to 58.62% for beach sediments, and 51.31% to 53.85% for estuarine sediments (Tables 12.1, 12.2, and 12.3). which is comparatively higher or lower than the hypothetical ilmenite (Deer et al. 1992) Higher titanium dioxide (TiO_2) concentration could result from the other cations in ilmenite leaching, while lower titanium dioxide (TiO_2) content could be the existence of exsolved phases of hematite (Jagannadha Rao et al. 2005). Detrital ilmenites from metamorphic sources have a narrow range of TiO_2 content, with a mean of roughly 47% TiO_2 (Basu and Molinaroli 1989).

FeO content varies from 32.97% to 48.58% (avg. 44.11%) in dune environments, from 44.21% to 49.41% (range 44.21–49.41%) in beach environments, and from 43.33% to 47.36% (range 43.33–47.36%) in estuarine environments (avg. 45.42%). The significant proportion of FeO in ilmenite may be due to exsolved stages of hematite. The MnO percentage of the ilmenite varies from 0.14% to 0.59% (avg. 0.31%) of sediments in beach environments, from 0.10% to 1.81% (avg. 0.48%) in dune environments, and from 0.15% to 2.72% in estuarine environments (avg. 0.54%). The MgO level varies from 0.05% to 1.32% (avg. 0.75%) in beach environments, from 0.06% to 1.56% (avg. 0.80%) in dune environments, and from 0.41% to 1.90% in estuarine environments (avg. 0.89%). In all conditions, ilmenite grains contain traces of SiO_2 (0.04%) and Al_2O_3 (0.02%) (Tables 12.1, 12.2, and 12.3).

The elemental geochemistry of ilmenite is very useful for geochemical characterization and elemental ratios such as manganese/magnesium are widely used as a provenance indicator. The manganese/magnesium ratio of ilmenites from beach sediments ranges from 0.31 to 7.10 (avg.1.65). More than 75% of the ilmenite samples show Mn/Mg ratio is ≤ 1. In the ilmenites of dune sediments, manganese/

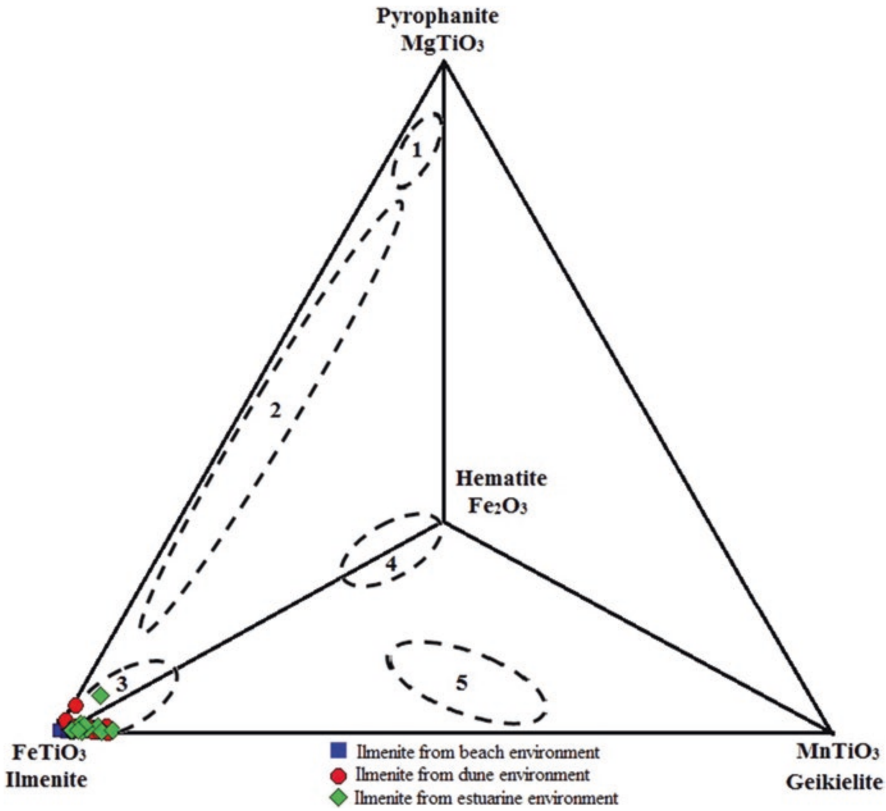

Fig. 12.3 Rhombohedral quaternary plot with a proportion of ilmenite, pyrophanite, hematite, and geikielite as poles (Haggerty 1976; Nayak and Mohapatra 1998). Ilmenites from beach, dune, and estuarine environment of the study area

magnesium ratio varies from 0.08 to 21.69 (avg. 3.64). More than 62% of ilmenite samples show manganese/magnesium ratio is ≤1 and in the ilmenite of estuarine sediments, manganese/magnesium ratio ranges from 0.12 to 4.45 (avg. 0.92) in the ilmenite of estuarine sediments (Table 12.4). More than 75% of ilmenites of estuarine environment also show a manganese/magnesium ratio of ≤1.

Several investigations on ilmenite of dunal sands Southwest coast of India and the Tamil Nadu coast indicate manganese/magnesium ratio is ≤1. The manganese/magnesium ratio of ilmenites from dune sands and source rocks of the southwest coast of India (Dinesh et al. 2007) is ≤1, and they suggested that the source rock for the ilmenites are mainly khondalite gneisses, and charnockites in the hinterland which was earlier reported by Aswathanaryana et al. (1964), Mallik et al. (1987), and Unnikrishnan (1988).

The manganese/magnesium ratio is ≤1, according to several studies on ilmenite of dunal sands on the Tamil Nadu and Southwest Indian coasts. Dinesh et al. (2007) suggested that the source rock for ilmenites is primarily khondalite gneisses and charnockites in the hinterland, which were previously reported by Aswathanaryana et al. (1964), Mallik et al. (1987), and Unnikrishnan (1988). Bhattacharyya et al. (1997) noticed that the high Manganese/Magnesium ratio > 9 for ilmenites from the Chhatrapur deposit corroborates the provenance of charnockites, migmatites, and granulites of Eastern Ghats as suggested earlier (Sengupta et al. 1990). The ratio of 2.56 for dune ilmenites of Visakhapatnam indicates various sources of basaltic and metasedimentary, rocks (Bhattacharyya et al. 1997). Ilmenites of Bhimunipatnam-Visakhapatnam coastal sands Manganese/Magnesium ratio ranges from 0.39 to 5.16 (Jagannadha Rao et al. 2005). The Manganese/Magnesium ratio of ilmenites from sapphirine granulite, charnockites, and khondalite of Eastern Ghat Group of rocks, Visakhapatnam is ≤1 (Kamineni and Rao 1988). Ilmenites of Chhatrapur (Acharya and Das 2001; Rao et al. 2005) and Ekakula dune sands (Acharya and Das 2001) of Orissa show a manganese/magnesium ratio of ≤1. The Tamil Nadu coastal ilmenites are mainly derived from metamorphic rocks. The manganese/magnesium ratios of ilmenites range from 1.69 to 3.59 in southeastern Bangladesh (Ahmed and Islam 2001) indicate that they are derived from plutonic rocks.

The present study area contains different suit of rock types such as khondalites, calc-silicate rocks, quartzites, charnockites, basic granulites, and granites of Archean to Precambrian age. These formations are highly migmatized and were termed as Eastern migmatized zone (Ramam and Murthy 1997). The manganese/magnesium ratios of the present work show that most of the ilmenites were derived from metamorphic rocks (pyroxene granulites and khondalites), the minor portion was derived from basic charnockites and migmatites.

Ilmenite‘s weathering mechanism has been proposed to be described by the ratio of Ti/(Ti + Fe). As the weathering mechanism progresses, the terms for the various stages are as follows: (a) Ti/(Ti + Fe) of ferrian ilmenite (0.50), (b) hydrated ilmenite (0.50–0.60), (c) pseudo rutile (0.60–0.70), and (d) leucoxene (>0.70) (Frost et al. 1983). In this work, ilmenite‘s chemical characterization and phases of modification were determined using the aforementioned classification.

The Ti/(Ti + Fe) ratio of the sediments from the beach environment ranges from 0.42 to 0.48 (avg. 0.46) (Table 12.4). These ilmenite grains have Ti/(Ti + Fe) ratio is <0.50 which indicates that they are ferrian ilmenite. In a dune environment, the Ti/(Ti + Fe) ratio of the sediments varies from 0.43 to 0.58 (avg.0.48) (Table 12.4) except for three samples all other ilmenite grains have Ti/(Ti + Fe) ratio is <0.50 which indicates that they are ferrian ilmenite. In an estuarine environment, the Ti/(Ti + Fe) ratio of the sediments average is 0.47and ranges from 0.46 to 0.49 (Table 12.4); these ilmenite grains have Ti/(Ti + Fe) ratio is <0.50 which indicates that they are ferrian ilmenite. The lower values of Ti/(Ti + Fe) and fresh grains of ilmenite indicate these grains have undergone less alteration.

Ilmenite’s degree of alteration is determined by the deposit’s geological history and weathering conditions (Hugo and Cornell 1991; Suresh Babu et al. 1994). Indian placer deposits have suffered varying degrees of change, with Kerala deposits showing the most alteration, Tamil Nadu deposits showing mild alteration, and Orissa deposits showing the least alteration (Suresh Babu et al. 1994). The present study area ilmenites have less alteration like ilmenites of Orissa placer deposits. The investigated area is under a subtropical environment. The high ferrous iron and less TiO_2 ilmenite compared to the west coast Manavalakurichi and Chavara deposits. It suggests that the present placer deposits are younger in age and have undergone the least weathering.

12.5 Conclusions

1. The end-member components of Fe-Ti oxides are mainly ilmenite and minor proportions of hematite, geikielite, and pyrophanite. The end-member compositions of Fe-Ti oxides and Manganese/Magnesium ratio indicate all the ilmenites of beach, dune, and estuarine environments are from the pyroxene granulites, khondalites, basic charnockites, and migmatites.
2. Ilmenites are ferrian types and Ti/(Ti + Fe) ratio is <0.5 indicating these are recently contributed to placer deposits.
3. Ilmenites are mainly concentrated in fine fraction (+230) 51.50%. Ilmenite contains average TiO_2 content is 52% with a low concentration of trace elements.

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