REE geochemistry of monazites from coastal sands between Bhimunipatnam and Konada, Andhra Pradesh, East coast of India

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The rare earth elements (REE) geochemistry of monazites of Bhimunipatnam–Konada coastal sand deposit was studied using EPMA method. The average LREE concentration was 53.31%, which is more than HREE (av 1.38%). ∑LREE more than actinides (Th + U) indicates that provenance for monazite in the study area is garnet-bearing paragenesis rocks such as charnockites and metapelitic rock (khondalite). The REE fractionation patterns and positive europium anomalies indicate that monazites were formed from magma/anatectic melt with high oxygen fugacity. The U–Th–Pb geochemical dating of monazites is 1000 Ma (average), which indicates that they are derived from protoliths of charnockites and metapelitic rocks such as khondalites, which are formed during meso–neo-Proterozoic ages in the Eastern Ghats Granulite Belt.

Keywords: Coastal sand deposits, geochemical dating, khondalites, monazites, rare earth elements.

MONAZITE is one of the important radioactive minerals associated with placer mineral deposits in India. It contains the radioactive element thorium and is a storehouse of the rare earth elements (REE). REE are a group of 17 metallic elements consisting of 15 lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) along with scandium and yttrium. REE are divided into two groups, i.e. lighter rare earth elements (LREE)–La to Sm, and heavier rare earth elements (HREE)–Gd to Lu. LREE + Sc is known as cerium group and HREE + Y as yttrium group. ThO_2 and REE contents of monazite are most important for its extraction for commercial purpose. REE concentration and distribution patterns are more significant compared to major and trace elemental abundance and distribution to understand the nature of the provenance of sediments[1,2]. REE abundance and distribution patterns in sediments indicate that their source rock.

Many researchers[3–19] have reported monazite occurrence and distribution from coastal sands in the present study area and in other parts of Andhra Pradesh (AP)[20–29] and Odisha coasts[30–35]. Few have made an attempt to study geochemistry of monazite in placer deposits of AP[2,24] and Odisha[1], while others[36–48] have reported geochemistry of monazites from various litho units of the Eastern Ghats Group of rocks.

The present study deals with REE geochemistry of monazite and its provenance of Bhimunipatnam–Konada placer deposit in northern Andhra Pradesh coast.

The 25 km coastal stretch of the study area (83°23′E to 83°36′E long. and 17°51′N to 18°02′N lat.) extends from the Pedda Gedda in the south to the Champavathi River in the north. The Gosthani River joins the Bay of Bengal at Bhimunipatnam. These ephemeral rivers originate in the Eastern Ghats hill ranges and constitute the drainage system. These rivers carry huge amounts of sediment and debouch into the Bay of Bengal at Chepala Uppada, Bhimunipatnam and Konada. The study area has different geological and geomorphic features generated by the rivers, small creeks and dynamic seasonal winds. The average width of coastal sand deposit is 980 m and dunes have maximum thickness of 18 m. At the 4 km south of Bhimunipatnam, an area of 10 km^2 covered with red sands extending 1.5–2.5 km inland from the beach and length of 5 km along the coast and other red sediment deposit occurring near Dibbalapalem, covered an area of 3.5 km^2 and extended 2 km along the coast and 1.2 km in land from the coast. Figure 1 shows the location map of the study area.

The Eastern Ghats Granulite Belt along the east coast of India extends over 1000 km. Major rock units in this granulite terrain are khondalites exhibiting compositional heterogeneity from sector to sector, and charnockites[36] and lesser abundance of basic granulites, intrusive alkaline rocks, anorthosites[49], pyroxene granulites, syn–post-tectonic granites[41], quartzites and leptynites.

A total of 25 surficial sediment samples (20 from coastal sands and five from red sediments) were collected along the Bhimunipatnam–Konada coast. Initially these samples were thoroughly washed with distilled water for removing the salts, treated with 15% hydrogen peroxide (H_2O_2) to remove organic matter and then with 10% dilute HCl to remove the shell material, and finally subjected to +230 mesh wet sieving. This was followed by the dry sieving into +60 (>0.25 mm), –60 to +120 (0.25 to 0.125 mm) and –120 to +230 (0.125 to 0.062 mm) ASTM mesh size fractions. The samples were subjected to heavy mineral separation using bromoform.

Monazites were identified under binocular petrological microscope based on their optical properties. Twenty-five grains were picked for geochemical analysis from coastal sands of Bhimunipatnam–Konada and red sediments.

CAMECA SX-100 Electron Probe Micro Analyzer (EPMA), Geological Survey of India, Hyderabad was used for geochemical analysis of monazite samples.

Thin sections of polished monazite grains of coastal sands (25) were selected for U–Th–Pb chemical dating using EPMA. The operating conditions for the analyses

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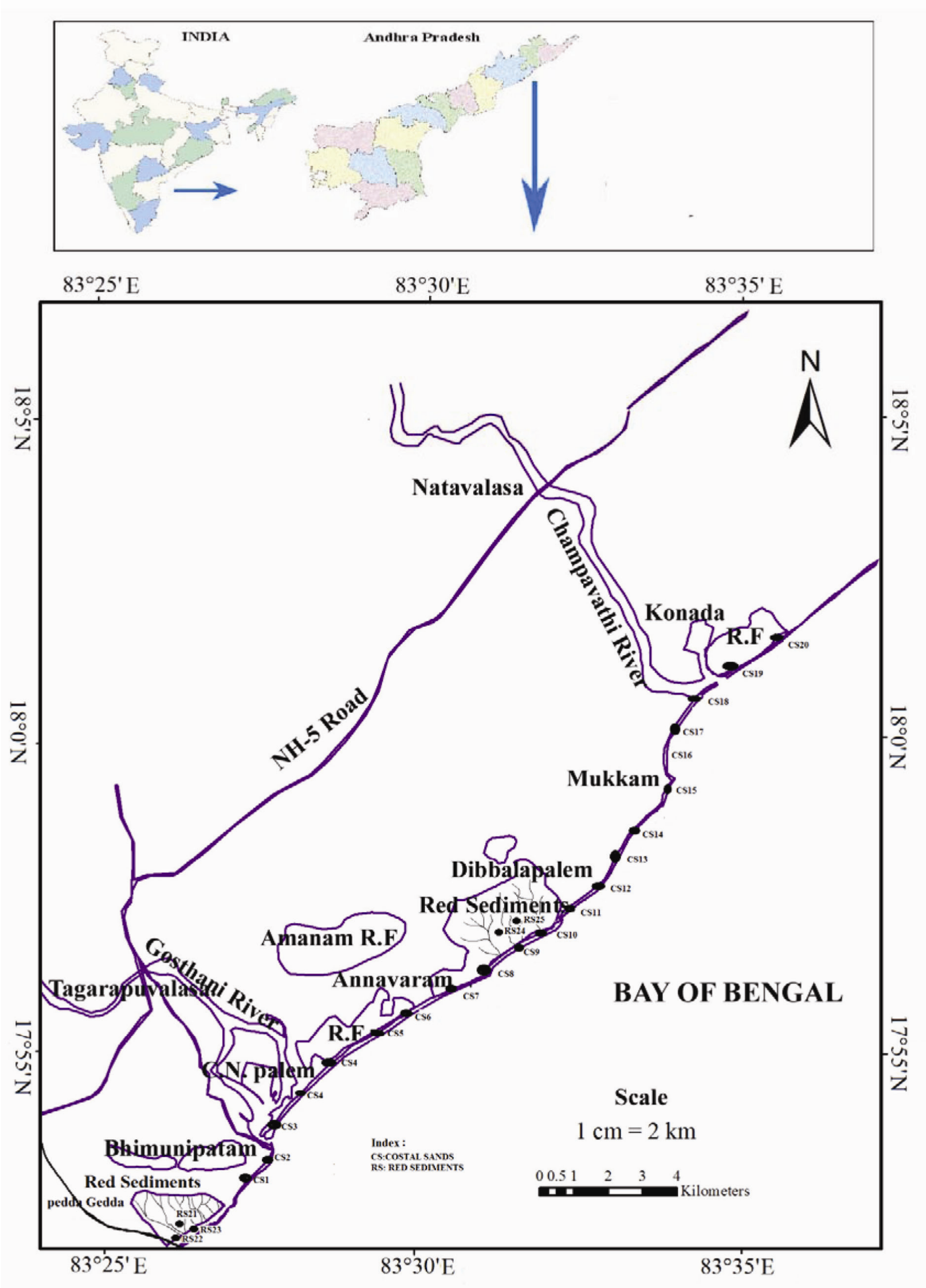

Figure 1. Sample location map of the study area.

were 20 kV of high voltage and 200 nA beam current with the minimum possible beam diameter. It was assumed that the characteristic X-rays were generated from a volume represented on the surface by an area of ~2 μm. Higher beam current was used for grains containing low thorium in order to have better statistics and lower errors. Calibrations were carried out at 20 kV and 200 nA while analysis was done at higher beam current (200–400 nA), PbMα was measured on Logarithmic Poisson Execution Time (LPET) and the peak counting time was 300 s with background measured on both sides. For uranium, the U(Mβ) line was used in order to avoid the interference of the Th(Mβ) line with a peak counting time of 200 s. U and Th were measured on PET crystal. Thorium Mα peak was also counted for 200 s. REE and the X-ray lines measured included La (Lα), Ce (Lα), Nd (Lα), Pr (Lβ), Sm(Lα), Ho (Lβ), Dy (Lα) and Gd (Lβ) on spectral analysis considerations arrived at using virtual EDS. Counting time at peak varied between 50 and 85 s for these elements. Y(Lα) line was used for yttrium and it was counted for 50s on peak. Interference of Y(Lc) on Pb(Mα) and ThMc on Pb(Mα) was corrected after measuring the interfering lines during calibration and thereafter applying the overlap correction. Other experimental conditions adopted here were similar to those reported in the literature[50–52]. Table 1 gives the geochemical data of monazite in the study area.

Monazite (La, Ce, Nd, Th, PO_4) is a phosphate of LREE and contains lesser amount of yttrium and HREE. The chemical composition of monazites of Bhimunipatnam–Konada coastal sand deposit is as follows: ThO_2 content varies from 3.78% to 13.39% (av 9.42%), Y_2O_3 from 0.00% to 2.26% (av 0.36%), SiO_2 from 0.48% to 2.85% (av 0.85%), CaO from 0.7% to 1.76% (av 1.29%), and UO_2 varies from 0.03% to 0.42% (av 0.13%) (Table 1). $\sum$REE ranges from 43.47% to 67.78% (av 54.69%), $\sum$LREE from 42.90% to 64.08% (av 53.31%), while $\sum$HREE average is 1.38% and its varies from 0.57% to 3.70% in the study area (Table 2).

In general, ThO_2 content in monazite is 4–12% and cheralite, a variety of monazite contains up to 30% ThO_2 (ref. 53). The average of ThO_2 content in studied samples is 9.42%; these are monazites not cheralites.

Khondalites from the Eastern Ghats Granulites Belt show uniform thorium content[39], but large variation is observed in charnockites of the Eastern Ghats Group of rocks[38]. From the khondalites suite of rocks, in monazites ThO_2 ranges from 6% to 10% and in monazite from charnockites, ThO_2 ranges between 9% and 10% (ref. 46). ThO_2 content in the 25 grains of monazites studied was <10% for 50% of the grains, while the remaining 50% grains showed >10% of ThO_2 content in the study area.

The heavy mineral assemblage of Bhimunipatnam–Konada placer mineral deposit with decreasing abundance is ilmenite, sillimanite, garnet, rutile, zircon, monazite and magnetite. The monazite grains are colourless to yellow, and are characterized by rounded to sub-rounded shape. Monazite grains show moderate relief, pits and etch marks.

The mineral assemblage of the study area is well correlated with mineralogical composition of the Eastern Ghats Group of rocks. The khondalite suite of rocks (garnet–quartz–sillimanite schist and gneiss and garnet ferous quartzite, leptynites, quartz granulites, calk silicate rocks and quartz–garnet–graphite–sillimanite schist) is a major lithological unit consisting of major minerals such as garnet ± biotite ± silimanite ± cordorite ± K-feldspar ± plagioclase feldspar + quartz and minor minerals magnetite, ilmenite, rutile, sphene, apatite and monazite[39]. The charnockite suite of rocks such as charnockites and enderbites, which consist of ortho and clino pyroxenes, garnet, biotite, magnetite, ilmenite, monazite, K-feldspar, plagioclase feldspar and quartz[38], and monazites of variable size (200–2000 μm) were noticed in charnockites and tiny (~50 μm) inclusions in garnet and cordierite[46] from the khondalite rocks.

In the present study, chondrite normalized values of REE [lighter lanthanides (LLn) and heavier lanthanides (HLn)] were used to understand the provenance of monazites[54]. REE Lu (0.85 Å)–La (1.06 Å) have higher charges and larger ionic radii and low concentration, showing little tendency to replace major elements during magmatic crystallization. Y and HREE have smaller ionic radii than LREE, due to which yttrium and HREE show low affinity for monazite crystal structure[55].

The ratio of $(\sum LLn/HLn)_{cn}$ in monazite of the coastal sands of the study area varies from 4.13 to 14.66 (Table 2), indicating preferential incorporation of lighter lanthanides relative to heaver lanthanides formed during partial melting[56]. $\sum$LREE/Th + U ranges from 5.70 to 28.33 (Table 1), which also supports substitutions of REE by Th and U (ref. 46).

The regression correlation analysis was carried out for chemical elements (Table 3) of monazites to understand the relation among different elements. LREE (La and Ce) showed significant positive correlation with calcium. Phosphorus has significant negative correlation with thorium and silicon. The HREEs such as Gd, Tb, Dy, Ho and Er showed significant positive correlation with yttrium.

Coupled ionic substitution such as $Ca^{+2} + Th^{+} \rightleftharpoons 2REE^{+3}$ and $Th^{+4} + Si^{+4} \rightleftharpoons P^{+5} + REE^{+3}$ was common. In order to understand these relationships, regression analysis was carried out between Th + Ca with LREE, REE and REE + Y and Th + Si with LREE + P, REE + P and REE + P + Y (Table 4) and which shows inverse relationships.

The correlation coefficients between (Th + Si) versus (P + LREE), (P + REE) and (P + REE + Y) of coastal sands showed negative relation amongst the X_i and Y_i components, which indicates substitution of these elements at major cation structural sites. The correlation coefficients of Th + Ca versus $\sum$LREE, $\sum$REE and $\sum$REE + Y of costal sands showed significant negative correlation and inverse relationship amongst X_i and Y_i components, indicating substitution (Table 4). These correlation coefficients show that Th + Si behaved similar to Th + Ca with similar regression coefficients. Thus, it indicates that Th + Si substitute P + LREE is another prime substitution in the analysed samples. The ratio $(La/Sm)_{Cn}$ in monazites varies from 1.60 to 10.33, which indicates that extended fractionation among the lighter lanthanides is less.

In the monazites from the coastal sands of Bhimunipatnam–Konada, Nd/Ce ratio varies from 0.34 to 0.39 and La/Ce varies from 0.38 to 0.57 (Table 2). These values are comparable to the values of monazites from Kalingapatnam–Baruva coast, Andhra Pradesh[24] and those from khondalite[45] and charnockites[43,46] of the Eastern Ghats of India as well as monazites from Eastern Minasas Gerias, Brazil[57].

Ce > Nd > La > Sm > Pr > Gd pattern is common in monazites[58]. The distribution pattern of REE in monazites

Table 1. Chemical data of monazites from Bhimunipatnam to Konada coastal sands (wt%)

Sample no.	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16	CS17	CS18	CS19	CS20	RS21	RS22	RS23	RS24	RS25	Min.	Max.	Av.
SiO_2	0.79	0.85	1.63	2.85	1.07	1.10	0.66	1.00	1.04	0.58	0.50	0.53	0.57	0.57	0.59	0.59	0.50	0.53	0.57	0.57	0.53	0.48	0.51	1.54	1.19	0.48	2.85	0.85
CaO	1.46	0.75	1.24	1.66	1.31	1.34	1.75	1.29	1.31	1.29	1.52	1.47	0.71	1.76	0.81	0.81	1.52	1.47	0.71	1.76	1.52	1.39	1.38	1.26	0.81	0.71	1.76	1.29
UO_2	0.28	0.08	0.05	0.03	0.08	0.07	0.15	0.09	0.10	0.42	0.09	0.09	0.07	0.15	0.08	0.08	0.09	0.09	0.07	0.15	0.31	0.23	0.23	0.06	0.04	0.03	0.42	0.13
ThO_2	9.02	8.36	12.00	13.39	10.05	10.12	11.86	11.16	11.85	11.00	10.88	10.12	8.87	10.01	8.12	3.78	8.57	8.59	3.98	10.01	8.6	7.58	7.56	11.75	8.32	3.78	13.39	9.42
PbO	0.42	0.24	0.53	0.59	0.44	0.43	0.42	0.25	0.25	0.36	0.39	0.39	0.18	0.41	0.17	0.17	0.39	0.39	0.18	0.41	0.42	0.37	0.37	0.51	0.37	0.17	0.59	0.36
P_2O_5	30.20	28.89	27.94	28.88	29.89	29.97	29.40	28.67	28.55	28.14	30.12	29.55	29.19	30.79	29.20	29.20	29.33	29.55	29.19	29.47	30.53	30.05	30.38	28.41	28.4	27.94	30.79	29.36
Y_2O_3	2.26	0.05	0.57	0.12	0.11	0.12	0.07	0.03	0.03	2.21	0.05	0.05	0.00	0.06	0.01	0.01	0.05	0.05	0.00	0.06	2.2	0.09	0.09	0.61	0.03	0.00	2.26	0.36
La_2O_3	10.50	17.18	11.55	8.79	11.39	10.40	10.50	13.25	13.12	12.15	11.19	11.21	12.45	10.38	13.47	13.47	10.60	11.21	12.45	10.38	9.73	12.53	12.4	11.87	13.72	8.79	17.18	11.83
Ce_2O_3	25.58	29.93	25.32	23.22	26.06	26.13	25.51	26.38	26.09	26.17	26.17	27.11	29.09	27.77	28.96	28.96	26.17	27.11	29.09	25.23	23.75	28.21	27.97	25.25	28.3	23.22	29.93	26.78
Pr_2O_3	2.85	2.50	2.61	2.94	2.96	2.93	2.98	2.54	2.56	3.21	3.58	2.96	3.22	2.89	2.94	2.94	2.92	2.96	3.22	2.89	2.72	3.09	2.93	2.63	2.8	2.50	3.58	2.91
Nd_2O_3	10.51	7.90	9.73	11.40	11.13	10.94	10.80	9.99	10.15	11.03	10.42	10.69	11.59	10.73	11.03	11.03	10.42	10.69	11.59	10.73	9.69	10.77	10.71	9.77	9.89	7.90	11.59	10.53
Sm_2O_3	1.74	0.49	1.33	1.57	1.31	1.31	1.32	1.05	0.98	1.14	1.22	1.15	1.30	1.36	1.44	1.44	1.22	1.15	1.30	1.36	1.8	1.11	1.08	1.36	0.78	0.49	1.80	1.25
Eu_2O_3	0.53	0.51	0.54	0.66	0.59	0.63	0.62	0.56	0.57	0.56	0.62	0.59	0.75	0.61	0.69	0.69	0.62	0.59	0.75	0.61	0.59	0.6	0.59	0.54	0.57	0.51	0.75	0.61
Gd_2O_3	1.20	0.20	0.62	0.45	0.45	0.42	0.23	0.18	0.19	0.23	0.18	0.20	0.16	0.29	0.15	0.15	0.18	0.20	0.16	0.29	1.19	0.2	0.38	0.82	0	0.00	1.20	0.35
Tb_2O_3	0.21	0.01	0.06	0.09	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.01	0.01	0.00	0.02	0.00	0.02	0.2	0.07	0	0.11	0	0.00	0.21	0.03
Dy_2O_3	0.67	0.05	0.20	0.12	0.07	0.12	0.05	0.03	0.04	0.06	0.05	0.00	0.00	0.05	0.00	0.00	0.05	0.00	0.00	0.05	0.65	0.07	0.05	0.19	0.05	0.00	0.67	0.10
Ho_2O_3	0.49	0.05	0.23	0.16	0.14	0.13	0.10	0.08	0.06	0.08	0.12	0.10	0.03	0.09	0.11	0.11	0.12	0.10	0.03	0.09	0.39	0.13	0.15	0.24	0.06	0.03	0.49	0.13
Er_2O_3	0.12	0.00	0.01	0.01	0.02	0.00	0.01	0.00	0.00	0.01	0.03	0.00	0.01	0.02	0.04	0.04	0.03	0.00	0.01	0.02	0.15	0	0.03	0.07	0	0.00	0.15	0.03
Tm_2O_3	0.18	0.04	0.13	0.09	0.12	0.14	0.10	0.10	0.06	0.12	0.10	0.09	0.12	0.15	0.12	0.12	0.10	0.09	0.12	0.15	0.16	0.07	0.12	0.15	0.08	0.04	0.18	0.11
Yb_2O_3	0.03	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.03	0.03	0.00	0.00	0.01	0.01	0.04	0.04	0.00	0.00	0.01	0.01	0.01	0.01	0	0.04	0.01	0.00	0.04	0.01
Lu_2O_3	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.01	0	0	0	0.00	0.02	0.00
Total	99.01	98.08	96.26	97.01	97.21	96.32	96.51	96.66	96.96	98.80	97.22	96.32	98.30	98.09	97.96	93.64	92.88	94.79	93.43	94.26	95.14	97.06	96.93	97.18	95.42	92.88	99.01	96.46
Number of cations on the basis of 4 oxygen atoms																												
Si	0.03	0.03	0.07	0.11	0.04	0.04	0.03	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06	0.05	0.02	0.11	0.03
Ca	0.06	0.03	0.05	0.07	0.06	0.06	0.08	0.06	0.06	0.06	0.06	0.06	0.03	0.07	0.03	0.04	0.07	0.06	0.03	0.08	0.06	0.06	0.06	0.05	0.04	0.03	0.08	0.06
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Th	0.08	0.08	0.11	0.12	0.09	0.09	0.11	0.10	0.11	0.10	0.10	0.09	0.08	0.09	0.07	0.03	0.08	0.08	0.04	0.09	0.08	0.07	0.07	0.11	0.08	0.03	0.12	0.09
Pb	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0.01	0	0.00	0.01	0.00
P	0.99	0.98	0.96	0.96	1.00	1.01	1.00	0.98	0.98	0.96	1.01	1.01	0.99	1.02	0.99	1.00	1.01	1.00	1.01	1.00	1.01	1	1	0.96	0.97	0.96	1.02	0.99
Y	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0	0	0.01	0	0.00	0.05	0.01
La	0.15	0.25	0.17	0.13	0.17	0.15	0.16	0.20	0.20	0.18	0.16	0.17	0.18	0.15	0.20	0.20	0.16	0.17	0.19	0.15	0.14	0.18	0.18	0.17	0.21	0.13	0.25	0.17
Ce	0.36	0.44	0.38	0.33	0.38	0.38	0.38	0.39	0.39	0.39	0.38	0.40	0.43	0.40	0.42	0.43	0.39	0.40	0.43	0.37	0.34	0.41	0.4	0.37	0.42	0.33	0.44	0.39
Pr	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04
Nd	0.15	0.11	0.14	0.16	0.16	0.15	0.16	0.14	0.15	0.16	0.15	0.15	0.17	0.15	0.16	0.16	0.15	0.15	0.17	0.15	0.14	0.15	0.15	0.14	0.14	0.11	0.17	0.15
Sm	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.02
Eu	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Gd	0.02	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0	0	0.01	0	0.00	0.02	0.00
Tb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Dy	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0	0	0	0	0.00	0.01	0.00
Ho	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.01	0.00
Er	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Tm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Yb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Lu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0.00	0.00	0.00
Total	1.99	1.99	1.99	1.97	1.98	1.97	1.98	1.98	1.98	2.00	1.98	1.98	1.98	1.98	1.99	1.95	1.95	1.95	1.97	1.93	1.94	1.96	1.94	1.96	1.97	1.93	2.00	1.97
∑LREE/Th + U	8.81	11.03	6.72	5.70	8.35	8.12	6.81	7.58	7.10	7.53	7.67	8.34	10.32	8.37	11.30	28.33	9.50	9.75	21.50	8.11	8.50	11.43	11.1	6.72	10.25	5.70	28.33	9.96
∑LREE/Y	15	780	60	266	320	289	537	1458	1342	16	782	686	9864	626	4399	DIV	DIV	DIV	DIV	DIV	13.	DIV	DIV	74	DIV	13	9864.	1266

CS, Coastal sands; RS, Red sediments.

Table 2. Chemical data of monazites from Bhimunipatnam to Konada coastal sands

Sample no.	∑LREE	Th + U (Acti)	∑REE	∑HREE	∑LREE/ HREE	REE + P	REE + P + Y	LREE + P	Nd/Ce	La/Ce	Th + Si	Th/U	Th + Ca	REE + Y	(La/Sm)cn	(∑LLn/HLn)cn
CS1	51.18	9.29	54.6	3.42	14.97	84.8	87.05	81.38	0.41	0.41	9.8	32.31	10.48	56.85	1.79	4.13
CS2	58	8.44	58.87	0.87	67.05	87.76	87.81	86.89	0.26	0.57	9.21	101.96	9.11	58.92	10.33	14.66
CS3	50.53	12.04	52.31	1.78	28.39	80.25	80.82	78.47	0.38	0.46	13.63	255.26	13.24	52.88	2.59	6.86
CS4	47.92	13.42	49.48	1.57	30.6	78.36	78.48	76.8	0.49	0.38	16.25	432.03	15.05	49.61	1.66	7.17
CS5	52.85	10.13	54.26	1.41	37.62	84.15	84.26	82.74	0.43	0.44	11.12	124.07	11.36	54.37	2.57	8.47
CS6	51.7	10.19	53.16	1.46	35.38	83.13	83.25	81.67	0.42	0.4	11.22	136.74	11.46	53.28	2.35	7.87
CS7	51.1	12.01	52.21	1.11	46.21	81.61	81.67	80.5	0.42	0.41	12.51	77.51	13.61	52.27	2.36	9.92
CS8	53.21	11.25	54.17	0.96	55.6	82.83	82.86	81.88	0.38	0.5	12.16	119.96	12.45	54.19	3.75	10.85
CS9	52.89	11.94	53.85	0.96	55.32	82.4	82.42	81.44	0.39	0.5	12.88	122.11	13.15	53.87	3.99	12.4
CS10	53.7	11.42	54.81	1.11	48.46	82.95	85.16	81.84	0.42	0.46	11.57	26	12.29	57.02	3.16	9.86
CS11	52.57	10.97	53.67	1.1	47.79	83.79	83.84	82.69	0.4	0.43	11.38	122.24	12.4	53.72	2.73	10.14
CS12	53.12	10.2	54.12	1	53.02	83.67	83.72	82.67	0.39	0.41	10.65	119.05	11.59	54.18	2.9	10.37
CS13	57.64	8.94	58.71	1.07	53.71	87.9	87.9	86.83	0.4	0.43	9.44	126.7	9.58	58.71	2.85	10.39
CS14	53.13	10.16	54.35	1.22	43.59	85.14	85.19	83.92	0.39	0.37	10.58	68.58	11.78	54.41	2.27	8.58
CS15	57.83	8.2	58.98	1.16	50.07	88.19	88.19	87.03	0.38	0.47	8.71	106.83	8.93	58.99	2.78	9.75
CS16	57.84	3.86	59	1.16	49.86	88.2	88.21	87.04	0.38	0.47	4.37	47.25	4.59	59.01	2.78	9.68
CS17	51.33	8.66	52.43	1.1	46.66	81.76	81.81	80.66	0.4	0.41	9.07	95.22	10.09	52.48	2.58	9.53
CS18	53.12	8.68	54.12	1	53.12	83.67	83.72	82.67	0.39	0.41	9.12	95.44	10.06	54.17	2.89	10.39
CS19	57.65	4.05	58.73	1.08	53.38	87.92	87.92	86.84	0.4	0.43	4.55	56.86	4.69	58.73	2.84	10.27
CS20	50.59	10.16	51.83	1.24	40.8	81.3	81.36	80.06	0.43	0.41	10.58	66.73	11.77	51.89	2.27	8.24
RS21	47.69	8.91	51.03	3.34	14.28	81.56	83.76	78.22	0.41	0.41	9.13	27.74	10.12	53.23	1.6	4.13
RS22	55.71	7.81	56.87	1.16	48.03	86.92	87.01	85.76	0.38	0.44	8.06	32.96	8.97	56.96	3.35	9.69
RS23	55.09	7.79	56.41	1.32	41.73	86.79	86.88	85.47	0.38	0.44	8.07	32.87	8.94	56.5	3.41	8.99
RS24	50.88	11.81	53.04	2.16	23.56	81.45	82.06	79.29	0.39	0.47	13.29	195.83	13.01	53.65	2.59	5.87
RS25	55.49	8.36	56.26	0.77	72.06	84.66	84.69	83.89	0.35	0.48	9.51	208	9.13	56.29	5.2	13.1
Min.	42.9	3.81	43.47	0.57	75.26	71.41	71.41	70.84	0.34	0.38	4.26	121.94	4.49	43.47	1.6	4.13
Max.	64.08	13.82	67.78	3.7	17.32	98.56	100.82	94.86	0.39	0.57	16.25	31.66	15.16	70.03	10.33	14.66
Av.	53.31	9.55	54.69	1.38	38.63	84.05	84.4	82.67	0.39	0.44	10.27	74.16	10.71	55.05	3.1	9.25

CS, Costal sands; RS, Red sediments.

Table 3. Correlation matrix for monazites of coastal sands from Bhimunipatnam to Konada ($n = 25$)

	Si	Ca	U	Th	Pb	P	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Si	1.00																				
Ca	0.05	1.00																			
U	–0.10	0.12	1.00																		
Th	0.57	0.50	0.30	1.00																	
Pb	0.59	0.17	0.34	0.69	1.00																
P	–0.71	0.24	–0.21	–0.49	–0.46	1.00															
Y	–0.06	0.09	0.58	0.10	0.13	–0.16	1.00														
La	–0.19	–0.74	–0.04	–0.37	–0.28	–0.26	–0.28	1.00													
Ce	–0.46	–0.70	–0.13	–0.65	–0.46	0.13	–0.46	0.81	1.00												
Pr	–0.23	–0.12	0.27	–0.10	0.07	0.25	0.04	–0.20	0.08	1.00											
Nd	–0.10	0.01	0.08	–0.21	–0.10	0.24	–0.11	–0.39	0.02	0.62	1.00										
Sm	0.04	0.29	–0.02	–0.04	0.15	0.21	0.25	–0.68	–0.42	0.22	0.53	1.00									
Eu	–0.23	–0.14	–0.66	–0.46	–0.51	0.23	–0.26	–0.10	0.18	0.12	0.35	0.23	1.00								
Gd	0.24	0.12	0.19	0.27	0.41	–0.10	0.76	–0.43	–0.65	–0.15	–0.26	0.34	–0.27	1.00							
Tb	0.34	0.16	0.41	0.17	0.32	–0.22	0.49	–0.30	–0.38	–0.11	–0.05	0.35	–0.49	0.51	1.00						
Dy	0.03	0.14	0.20	0.05	0.05	0.09	0.81	–0.39	–0.55	–0.14	–0.22	0.31	–0.22	0.90	0.57	1.00					
Ho	0.29	0.17	0.53	0.30	0.47	–0.13	0.42	–0.29	–0.38	0.03	–0.02	0.29	–0.69	0.50	0.89	0.51	1.00				
Er	–0.05	0.06	0.50	0.01	0.23	0.07	0.44	–0.19	–0.18	0.11	0.00	0.34	–0.43	0.44	0.81	0.51	0.85	1.00			
Tm	0.19	0.11	0.67	0.43	0.55	–0.08	0.23	–0.24	–0.21	0.24	0.17	0.15	–0.71	0.28	0.51	0.21	0.77	0.59	1.00		
Yb	–0.07	–0.10	0.64	0.12	0.15	–0.14	0.37	0.02	–0.02	0.09	0.17	0.11	–0.35	0.16	0.31	0.19	0.45	0.51	0.54	1.00	
Lu	0.00	–0.25	0.40	0.03	0.13	–0.22	0.17	0.43	0.17	–0.03	–0.33	–0.43	–0.47	–0.01	–0.08	–0.06	0.03	–0.02	0.13	0.05	1.00

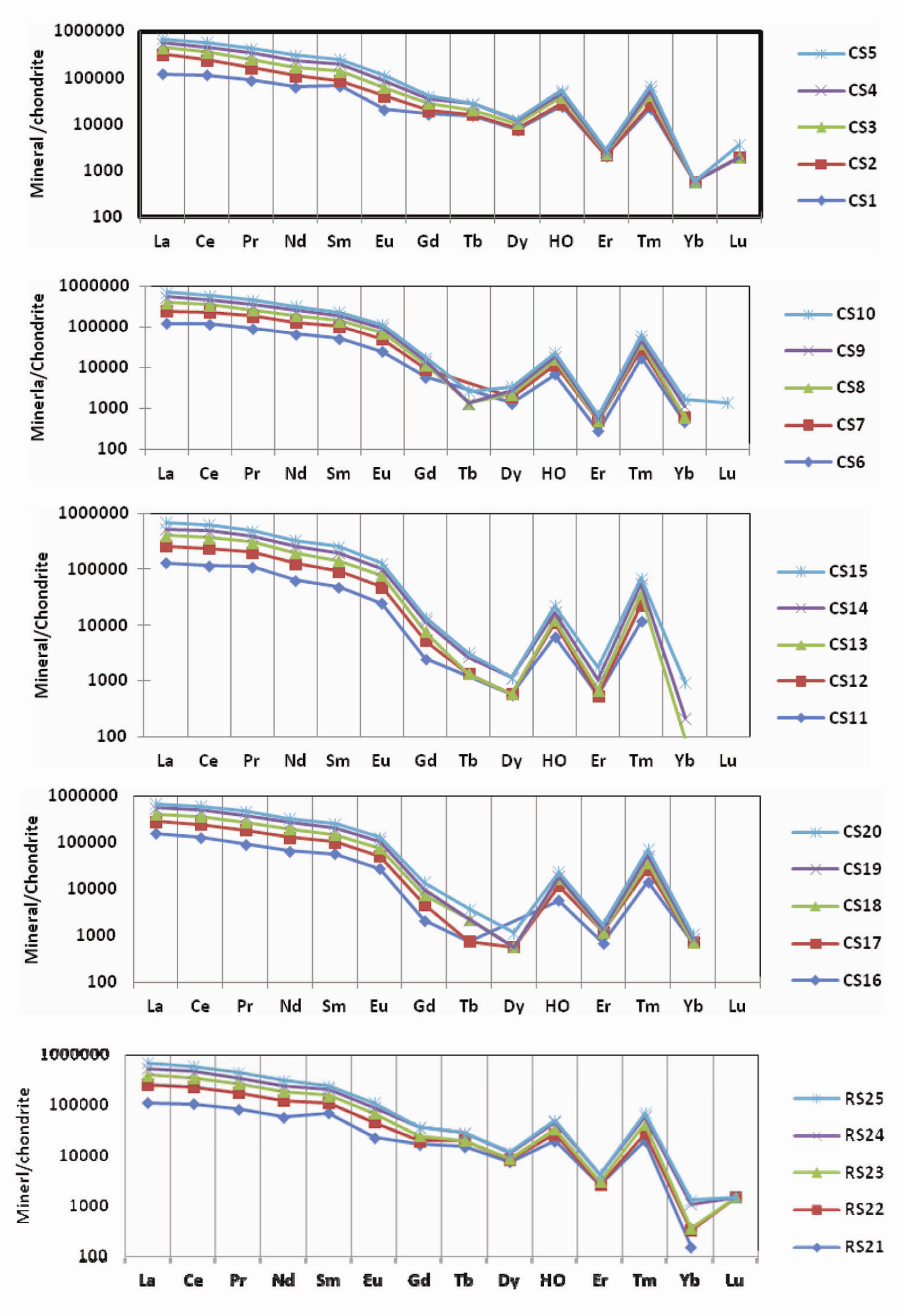

Figure 2. Chondrite-normalized (chondrite values from Taylor and McLennan[54]) patterns of REEs for monazite of coastal sands from Bhimunipatnam to Konada.

of the study area is Ce > La > Nd > Pr > Sm > Gd. Similar distribution patterns in monazite were observed in different litho units from the Eastern Ghats Granulite (EGG) Belt[46] and Kalingapatnam–Baruva coastal sands[24]. However, the monazite grains contain greater LREE than HREE content and less yttrium concentration. In general, monazite associated with garnet has less affinity towards yttrium and HREE[46,59].

Figure 2 shows the chondrite-normalized REE distribution patterns of individual monazite grains from coastal sands and red sediments for the study area.

REE distribution pattern in monazites is influenced by geological evolution mainly mineral phase assemblage, and source-rock material from which the monazites were formed[60]. The monazite sands of the study area showed positive europium (Eu) anomaly. The negative or positive anomalies are a reflection of enrichment/depletion of Eu in progressive crystallization of magma or anatectic melt under high oxygen fugacity (more oxidation conditions) or reduction conditions[56]. Magnetite is one of the important accessory minerals in the khondalite and charnockite suite of rocks, which indicates high oxidation conditions during crystallization of anatectic melt of khondalites and crystallization of magma for charnockites. In the more oxidation conditions of magma, europium is in the Eu^{+3} state, which does not incorporate in the plagioclase feldspars but at less oxidizing conditions, europium is in the Eu^{+2} state and it will enter into the plagioclase feldspars. So the enrichment of Eu^{+3} in the magma in relation to REE gives positive anomalies in the chondrite-normalized REE patterns of monazites. In the Eastern Ghats Group of rocks, the magnetite content and REE patterns in charnockites of enderbites nature of Visakhapatnam region show Eu positive anomaly indicates that charnockites protolith were formed under high oxygen fugacity of magma and most of charnockites of AP are calc-alkaline magmas, which are in general more oxidized[38]. The monazite associated with charnockites and the monazite inclusions in garnets of the khondalites show positive Eu anomaly, but the monazites in pyroxene granulites show negative Eu anomalies[45]. The positive Eu anomaly of monazites in the study area indicates that these are derived from charnockites and tiny inclusions in garnet occurring in the khondalites.

Table 4. Correlation coefficients of chemical data from Bhimunipatnam to Konada coastal sands

	Th + Ca		Th + Si
LREE (La–Sm)	–0.810	LREE + P	–0.763
REE	–0.827	REE + P	–0.792
REE + Y	–0.824	REE + P + Y	–0.832

Table 5. U–Th–Pb geochemical dating of monazites from coastal sands of Bhimunipatnam–Konada

Sample no.	Age (Ma)
CS1	968 ± 50
CS2	835 ± 57
CS3	1003 ± 47
CS4	1014 ± 46
CS5	990 ± 50
CS6	984 ± 50
CS7	926 ± 48
CS8	1114 ± 37
CS9	1024 ± 37
CS10	1018 ± 56
CS11	1019 ± 55
CS12	1006 ± 34
CS13	1003 ± 53
CS14	904 ± 87
CS15	981 ± 84
CS16	981 ± 84
CS17	1019 ± 56
CS18	1007 ± 54
CS19	1003 ± 83
CS20	903 ± 47
RS21	1006 ± 52
RS22	1021 ± 56
RS23	1019 ± 56
RS24	999 ± 48
RS25	1002 ± 55
Min.	835 ± 34
Max.	1114 ± 87
Av.	990 ± 55

CS, Coastal sands; RS, Red sediments.

Table 5 provides data on the U–Th–Pb geochemical dating of monazite grains of coastal sands carried out in the present study. The age of monazite grains of coastal sands ranges from 835 ± 34 to 1114 ± 87 Ma.

The age of monazites from various rock types of the EGG Belt of India ranges from 1600 to 500 Ma, in response to tectonic–metamorphic events. Average age of studied monazite grains is 1000 Ma. Similar ages for monazites were noted in khondalites (990–965 Ma) and charnockite complex (980–910 Ma) of the respect drainage basins of the Gosthani and Champavathi rivers[42] and adjacent drainage basins of the Nagavali River in the study area, which is part of zone-II and zone-III isotopic domains of the Eastern Ghats[61].

In the Eastern Ghats two ages for protoliths emplacement have been recorded[62], i.e. middle Proterozoic ~1000 Ma. The charnockites of the Eastern Ghats are subjected to two periods of protolithic intrusions, one in palaeo-Proterozoic and the other in meso–neo Proterozoic[62]. Therefore, the monazite grains might be derived from charnockites formed during meso–neo Proterozoic and/or garnet-bearing metapelitic rock (khondalites) which are formed in high-grade metamorphism during the same time.

Thus ThO_2 content in monazites of Bhimunipatnam–Konada coastal sands varies from 3.78% to 13.39% with an average of 9.42%, indicating these are monazites and not cheralites. ThO_2 content indicates that almost 50% of the studied grains are from metapelitic rocks and the remaining are from the charnockite suite of rocks.

All the monazites studied show characteristic feature that the total REE is more than actinides (U + Th). In general, the garnet-bearing paragenesis rocks the HREE preferred to enter into garnets along with yttrium than other minerals.

The greater LREE content compared to HREE content with less yttrium concentration in monazites of coastal sands indicates that it is derived from metapelitic khondalites and charnokites in the study area, showing garnet-bearing paragenesis.

The U–Th–Pb geochemical dating of monazites in the study area indicates that the age of monazite grains is about 1000 Ma. These grains might be derived from second phase (meso–neo-Proterozoic) of protolithic intrusions, i.e. charnockites which are present surrounding the study area and metapelitic rocks formed in the period

950–1100 Ma of the Main Eastern Ghats Orogeny (Grenville) accompanied by pervasive metamorphism, which causes monazite formation in khondalites of the same age.

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ACKNOWLEDGEMENTS. We thank the authorities of Department of Geology, Andhra University, Visakhapatnam, and Geological Survey of India, Hyderabad for providing lab facilities (CAMECA SX-100 Electron Probe Micro Analyzer) to carry out geochemical analysis, and CSIR, New Delhi for financial assistance to K.B.N. in the form of SRF.

Received 5 September 2015; revised accepted 29 December 2015

doi: 10.18520/cs/v110/i8/1550-1559

Forage and security trade-offs by markhor *Capra falconeri* mothers

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Food acquisition and security from predators are primary determinants of habitat use in ungulates. There is usually a trade-off in the response of animals to these two factors, influenced by the individual's reproductive state. Females with vulnerable offspring, after parturition, are expected to compromise food acquisition for security. In temperate species such as the markhor *Capra falconeri*, however, the females give birth at a time when nutritious forage begins to

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