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SHORT COMMUNICATION

Rutile Mineral Chemistry as a Guide to Provenance of Red Sediments and Modern Sands of Bhimunipatnam–Konada Coast, Andhra Pradesh, East Coast of India

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Abstract Rutile is the most stable and widely distributed TiO_2 polymorph in rocks of low- to high-grade metamorphic facies and is also an accessory mineral in igneous rocks. Rutile is commonly available in modern to ancient placer mineral deposits in the coastal sediments. Mineral chemistry of rutile from red sediments and modern sands along Bhimunipatnam–Konada coast were used in the present study to know its provenance. Iron (Fe), chromium (Cr), niobium (Nb) content and their distribution pattern in rutile and also their relationships with aluminum (Al) and magnesium (Mg) concentrations provide information on its provenance. These study reveals that the Fe–Cr and Cr–Nb systematics indicates majority of rutiles were derived from metapelitic rocks mainly khondalites and leptynites of the Eastern Ghats Granulite Belt (EGGB) and minor contribution is from magmatic charnockites, pegmatites and granites. The Al and Mg behavioral pattern in rutile from both zones clearly depicts that the most of the rutiles are derived from crustal rocks. The rutile contribution to late quaternary red sediments and modern coastal sands is also from same provenance.

Keywords Rutile · Red sediments · Modern coastal sands · Khondalites · Charnockites

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For the last few decades, recent development in mineral–chemical provenance studies concerns advance in understanding of the mineral chemistry of rutile. Rutile mineral chemistry was used for genetic information [1]. Rutile predominantly forms in medium- to high-grade metamorphic rocks, although it has been recorded in plutonic rocks, such as granitoids and anorthosites [2]. It is scarce or absent in most of igneous and low-grade metamorphic rocks [3, 4]. The large variation in major elemental composition of rutile geochemistry is used in provenance studies. Detrital rutile in Triassic continental red-beds has been studied in beryl field [5, 6]. North Sea comprises almost pure TiO_2, with only small proportion containing appreciable amount of Nb_2O_5, Ta_2O_5 or FeO.

Electron probe microanalyzer data on rutile indicate that a large number of trace elements (Fe, Cr, Al, Mg, Nb, Ta) may substitute Ti in the rutile lattice [7–15] and the trace elements signature could be used as a provenance indicator. Detrital rutile geochemical studies by Meinhold et al., Stendal et al. and Triebold et al. [13, 16, 17] have demarcated the effectiveness of the method in identifying source and containing the metamorphic evolution of the hinterland. Rutiles were discriminated from crustal and mantle derived sources [10].

The chemical analysis of detrital rutiles may yield significant provenance information which is of particular importance because of stability of rutile under both burial diagenetic and surficial weathering conditions [18–20]. Previous investigators [9, 13, 16, 17, 21] have been undertaken rutile geochemistry studies effectively identification for provenance.

This paper deals with detrital rutile geochemistry as guide to provenance of red sediments and modern sands of Bhimunipatnam–Konada coast, Andhra Pradesh, East Coast of India. In India, detrital rutile mineral chemical studies have been taken Kerala beach sands [22]. The occurrence of rutiles has been reported in charnockites, khondalites and pyroxene granulites of Eastern Ghat Group of rocks [23].

The present study area is bounded by longitude 83°23′ to 83°36′E and latitude 17°51′ to 18°02′N. Major rivers flowing in the study area are Champavathi and Gosthani. These ephemeral rivers originate in the Eastern Ghat hill ranges, constitute the drainage system, carry huge amount of sediment, and debouch in to the Bay of Bengal at Bhimunipatnam and Konada in the study area. The coastal stretch of extending for 25 km the study area extends from the Gosthani River in the South to the Champavathi River in the North both are joins into Bay of Bengal. These ephemeral rivers originate in the Eastern Ghat hill ranges and constitute the drainage system and carry huge amount of sediment and debouch in to the Bay of Bengal at Bhimunipatnam and Konada in the study area. The study area has different geological and geomorphic features generated by the rivers, small creeks, altered coastal trends, and dynamic seasonal winds. In the study area, average width of coastal sand deposit is 980 m and dunes with maximum thickness of 18 m. Predominantly red-looking sands covering an area of 10 km^2 are popularly known as Bhimunipatnam “Red Sediments.” These sands extend 1.5–2.5 km inland from the beach and 5 km along the coast at the 4 km south of Bhimunipatnam. Selected sample locations for provenance studies are given in Fig. 1A.

The Eastern Ghats Granulite Belt along the east coast of India extends for over 1000 km. Major rock units in this granulite terrain are khondalites exhibiting compositional heterogeneity from sector to sector and charnockites [24] and lesser abundances of basic granulites, intrusive alkaline rocks, anorthosites [25], pyroxene granulites, syn–post–tectonic granites [26], quartzites and leptynites.

During the study, a total of ten samples were collected from the red sediments and modern coastal sands. These collected samples were sun-dried, later representative sediment samples were reduced by coning and quartering method, heavy mineral separation was done by using bromoform, and the rutile mineral grains were identified under binocular petrological microscope based on their optical properties and picked for geochemical analysis (EPMA). Thirty rutile grains (twelve from yellow sand unit, six from reddish brown unit and twelve from brick red sand unit) from different sand units of red sediments and thirty rutile grains from modern sands of Bhimunipatnam–Konada coast were selected for chemical analysis.

The mineral grains were analyzed using a CAMECA SX-100 electron probe microanalyzer (EPMA), housed at the Geological Survey of India (GSI), Hyderabad. Polished surfaces of rutile grains were exited by an electron beam with an accelerating voltage of 15 kV and the beam current 20 nA. The beam radius was kept at $\sim$ 1 μm. For calibration, natural mineral standards were used for most of the elements (Orthoclase for Si and K; Corundum-Al; Wollastonite-Ca; Haematite-Fe; Apatite-P; Chromite-Cr; Albite for Na and Al; Diopside for Mg and Ca; Apatite-P; Rhodonite-Mn; TiO_2-Ti; Almandine-Fe; Nb on Nb and Ta on Ta). Mineral chemical data of detrital rutile from red sediments and modern sands of Bhimunipatnam–Konada coast are given in Table 1.

Rutile is one of the important economic heavy minerals for titanium, and it forms in high-grade metamorphic rocks such as granulites and eclogite facies of rocks. Rutile is widely distributed in many igneous and plutonic rocks, but placer deposits are the main source of extraction of rutile for economic purpose, and to understand its industrial suitability, geochemistry of rutiles was studied.

Rutile is one of the important stable detrital minerals in sedimentary environments and mainly consists of titanium dioxide (TiO_2) and important carrier of Nb, Cr, Ta, V, Mo, Sn, Sb, and W elements [7, 27]. The information contained in rutile is most important to study the maturity of sediments. In recent times, many scientists made an attempt on provenance studies based on rutile mineral chemistry.

Heavy minerals are a significant tool to interpret the provenance, source of rock, transportation history of continental-beach-dune-shallow marine sediments [28].

The photomicrographs of rutile grains are red, blood red and reddish brown in color with rounded (a, b), anhedral (c, d) and prismatic (e, f) in shape (Fig. 1B a–f) grains with well-developed terminations or breakage patterns; sometimes thick halo surrounds the grains and very high relief and distinct pleochroism. Occasionally, striations are observed.

The rounded and sub-rounded grains of rutile indicate long distance of transportation and reworked nature. The sub-angular grains of rutiles indicate that they might have been derived from nearby sources, i.e., mainly khondalite and charnockites.

The TiO_2 content of red sediments ranges from 97.68 to 99.78% (av. 98.66%) and the TiO_2 content of rutiles of

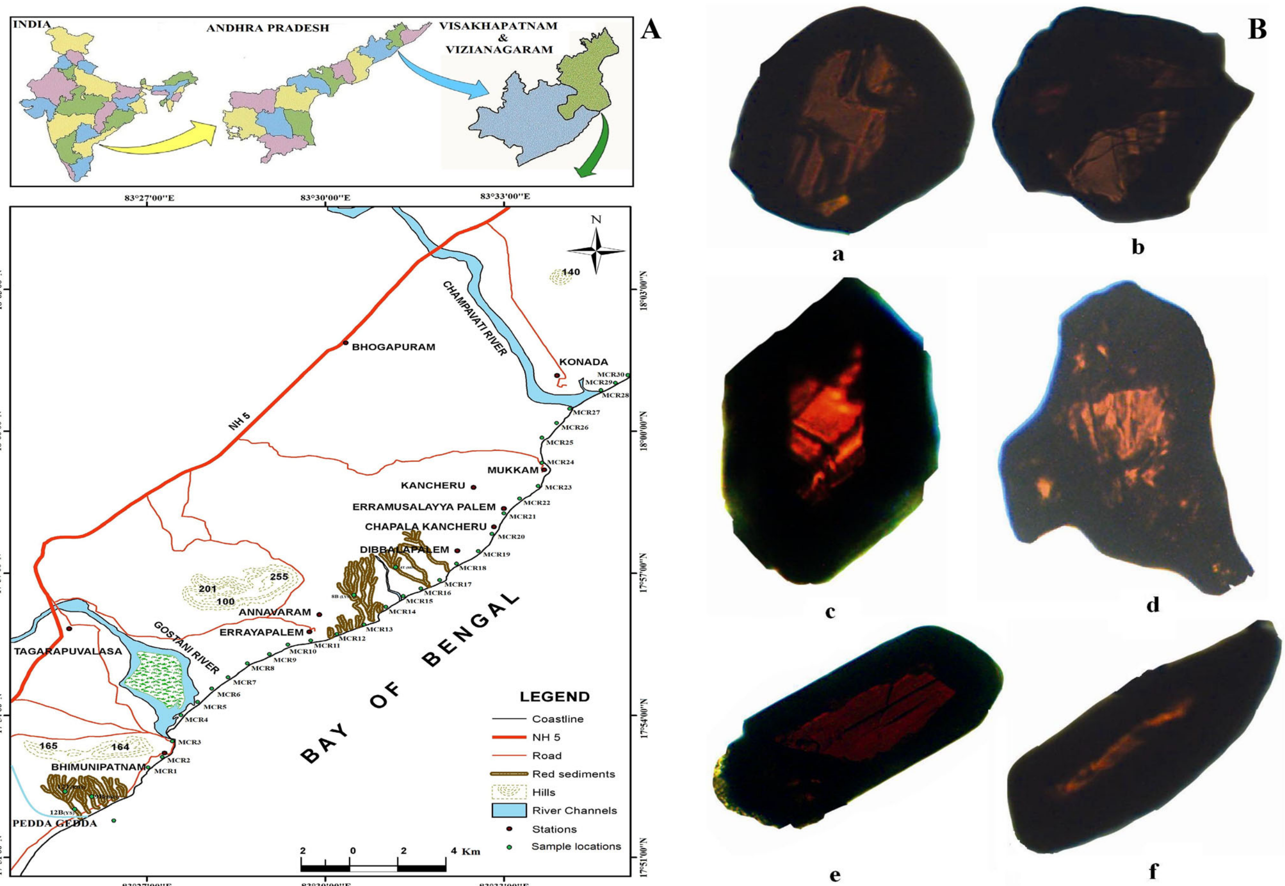

Fig. 1 **A** Map of the study area and **B** rutile grains (a–f)

modern sands of Bhimunipatnam–Konada coast ranges from 97.48 to 99.13% (av. 98.10%).

The Fe content of rutiles of red sediments ranges from 70 to 2332 ppm (av. 864.33 ppm). The Cr content of rutiles of red sediments ranges from 629 to 12302 ppm (av. 2826 ppm). The Nb content of rutiles of red sediments ranges from 16 to 9664 ppm (av. 3640).

The Fe content of rutiles of Bhimunipatnam–Konada modern coastal sands ranges from 8 to 1096 ppm (av. 435 ppm). The Cr content of rutiles of modern sands ranges from 424 to 8402 ppm (av. 2589 ppm). The Nb content of rutiles of modern sands ranges from 79 to 8551 ppm (av. 3708 ppm).

Cr versus Fe systematics is not established thoroughly, but an attempt was made to differentiate rutiles based on Fe and Cr contents [9]. Rutiles with Fe content < 1000 ppm and Cr content > 3000 ppm are considered to be derived from magmatic rocks [9]. In order to understand provenance of rutiles of red sediments and modern coastal sands, the Cr versus Fe scatter plots and phi charts show 20% of analyzed samples of red sediment rutiles fall in magmatic zone, while remaining 80% fall in metamorphic zone (Fig. 2a) and 17% of analyzed samples of modern coastal sand rutiles fall in magmatic zone and remaining 83% of analyzed samples of rutiles fall in metamorphic zone (Fig. 2b) of the study area.

The concentration of Nb and Cr in rutile can be used to distinguish rutile formed in metamafic and metapelitic rocks. The Nb content in metapelites ranges from 900 to 2700 ppm [29, 30]. Scatter plot of Nb versus Cr [21] was used to differentiate whether rutiles are derived from metapelitic rocks or from metamafic rocks.

Nb versus Cr scatter plot [21] was used to differentiate whether rutiles are derived from metapelitic rocks or from metamafic rocks. Nb versus Cr diagram and phi charts (Fig. 2a) show 71% of analyzed samples of red sediments, indicating that they are derived from metapelitic rocks and remaining 29% from metamafic rocks, and modern coastal sands of Nb versus Cr diagram (Fig. 2b) show 64% of analyzed samples of red sediments, indicating that they are derived from metapelitic rocks and remaining 36% from metamafic rocks; both show mixed rutile source with more pronounced metapelitic rocks and minor contribution from metamafic rocks of the study area.

Table 1 Chemical composition of rutiles from red sediments and modern coastal sands of Bhimunipatnam–Konada coast (Wt%)

	MCR1	MCR2	MCR3	MCR4	MCR5	MCR6	MCR7	MCR8	MCR9	MCR10	MCR11	MCR12	MCR13	MCR14	MCR15
SiO_2	0.02	0.01	0.00	0.21	0.02	0.05	0.00	0.02	0.01	0.04	0.01	0.02	0.00	0.01	0.03
TiO_2	97.48	97.68	98.26	97.61	98.24	98.91	97.98	98.21	98.26	98.48	97.98	97.75	98.35	98.65	97.74
Al_2O_3	0.55	0.06	0.01	0.00	0.01	0.00	0.03	0.03	0.03	0.01	0.01	0.03	0.01	0.01	0.01
FeO	0.04	0.08	0.07	0.09	0.13	0.22	0.11	0.03	0.11	0.03	0.02	0.00	0.01	0.03	0.07
MnO	0.02	0.01	0.02	0.00	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.00	0.09	0.02
MgO	0.00	0.01	0.01	0.14	0.01	0.03	0.00	0.02	0.01	0.00	0.02	0.03	0.01	0.00	0.00
CaO	0.04	0.01	0.02	0.03	0.01	0.04	0.01	0.03	0.03	0.02	0.00	0.03	0.01	0.02	0.01
Na_2O	0.03	0.01	0.01	0.02	0.01	0.03	0.01	0.02	0.02	0.02	0.01	0.00	0.01	0.02	0.01
K_2O	0.01	0.01	0.02	0.01	0.03	0.01	0.00	0.00	0.02	0.00	0.01	0.02	0.02	0.01	0.00
Cr_2O_3	0.15	0.04	0.21	0.11	0.07	0.09	0.19	0.27	0.14	0.16	0.61	0.18	0.19	0.34	0.24
Nb_2O_3	0.26	0.23	0.01	0.13	0.16	0.41	0.34	0.32	0.34	0.19	0.22	0.41	0.23	0.21	0.07
Ta_2O5	0.04	0.04	0.03	0.04	0.03	0.00	0.00	0.04	0.00	0.04	0.02	0.04	0.03	0.01	0.07
P_2O_5	0.01	0.00	0.00	0.04	0.01	0.05	0.03	0.00	0.02	0.01	0.02	0.05	0.04	0.05	0.02
Total	98.66	98.19	98.66	98.44	98.77	99.85	98.71	98.99	98.99	99.01	98.95	98.57	98.89	99.46	98.30
Number of cations on the basis of 4(O)															
Si	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	0.00
Al	0.02	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
Ti	1.98	1.99	1.99	1.98	1.99	1.99	1.99	1.99	1.99	1.99	1.98	1.99	1.99	1.99	1.99
Fe	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
Mn	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
Mg	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	0.00
Ca	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
Na	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
K	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
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01
Nb	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
Ta	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
P	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
Total	2.01	2.00	2.00	2.01	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

	MCR16	MCR17	MCR18	MCR19	MCR20	MCR21	MCR22	MCR23	MCR24	MCR25	MCR26	MCR27	MCR28	MCR29	MCR30
SiO_2	0.02	0.01	0.02	0.05	0.04	0.01	0.03	0.00	0.05	0.02	0.01	0.01	0.03	0.01	0.00
TiO_2	97.80	97.83	98.40	97.58	97.72	98.14	99.13	98.34	97.71	98.43	97.91	98.03	98.41	97.73	98.31
Al_2O_3	0.01	0.02	0.01	0.01	0.07	0.01	0.01	0.02	0.03	0.03	0.04	0.01	0.00	0.02	0.02
FeO	0.04	0.07	0.03	0.14	0.11	0.04	0.02	0.04	0.11	0.08	0.23	0.11	0.17	0.14	0.07
MnO	0.00	0.04	0.01	0.00	0.01	0.02	0.03	0.09	0.02	0.00	0.01	0.01	0.06	0.03	0.04
MgO	0.02	0.00	0.02	0.01	0.01	0.00	0.00	0.03	0.01	0.02	0.01	0.00	0.00	0.02	0.02
CaO	0.01	0.04	0.02	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.03	0.02	0.03	0.01	0.01
Na_2O	0.00	0.01	0.01	0.04	0.01	0.01	0.03	0.02	0.00	0.02	0.01	0.01	0.00	0.02	0.01
K_2O	0.02	0.00	0.00	0.02	0.01	0.02	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.00	0.02
Cr_2O_3	0.18	0.09	0.10	0.14	0.11	0.20	0.03	0.06	0.16	0.12	0.10	0.29	0.12	0.21	0.19
Nb_2O_3	0.13	0.01	0.07	0.22	0.54	0.43	0.09	0.12	0.26	0.25	0.36	0.45	0.07	0.53	0.20
Ta_2O_5	0.06	0.01	0.09	0.00	0.04	0.00	0.03	0.07	0.02	0.00	0.06	0.10	0.02	0.03	0.02
P_2O_5	0.02	0.04	0.00	0.05	0.02	0.01	0.01	0.03	0.00	0.03	0.00	0.03	0.01	0.04	0.03
Total	98.29	98.16	98.78	98.26	98.68	98.90	99.41	98.83	98.39	99.03	98.78	99.09	98.92	98.79	98.94
Number of cations on the basis of 4(O)															
Si	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
Al	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
Ti	1.99	1.99	1.99	1.99	1.98	1.99	2.00	1.99	1.99	1.99	1.99	1.98	1.99	1.98	1.99
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Mn	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
Mg	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
Ca	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

Table 1 continued

	MCR16	MCR17	MCR18	MCR19	MCR20	MCR21	MCR22	MCR23	MCR24	MCR25	MCR26	MCR27	MCR28	MCR29	MCR30
Na	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
K	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
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Nb	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
Ta	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
P	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
Total	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Sample no	12T (reddish brown sands)						4T (brick red sands)						9B (brick red sands)					
Grain no	RBI	RB2	RB3	RB4	RB5	RB6	BR1	BR2	BR3	BR4	BR5	BR6	BR1	BR2	BR3	BR4	BR5	BR6
SiO_2	0.00	0.01	0.00	0.01	0.03	0.02	0.00	0.00	0.01	0.02	0.01	0.05	0.03	0.00	0.01	0.01	0.02	0.03
TiO_2	98.60	99.29	98.76	99.10	98.31	99.78	98.91	98.96	98.91	98.81	99.27	97.99	98.80	98.47	99.60	98.83	98.11	98.81
Al_2O_3	0.00	0.05	0.04	0.01	0.02	0.03	0.03	0.00	0.04	0.01	0.03	0.03	0.00	0.03	0.01	0.00	0.01	0.02
FeO	0.05	0.20	0.18	0.03	0.30	0.14	0.11	0.08	0.11	0.05	0.08	0.23	0.23	0.01	0.13	0.14	0.13	0.01
MnO	0.06	0.05	0.02	0.01	0.02	0.01	0.00	0.07	0.01	0.01	0.04	0.09	0.05	0.01	0.02	0.03	0.00	0.03
MgO	0.01	0.02	0.01	0.01	0.01	0.01	0.03	0.01	0.00	0.02	0.01	0.01	0.02	0.00	0.02	0.01	0.01	0.02
CaO	0.01	0.01	0.03	0.01	0.02	0.01	0.03	0.01	0.01	0.02	0.05	0.01	0.00	0.02	0.03	0.00	0.01	0.04
Na_2O	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.00	0.04	0.02	0.02
K_2O	0.01	0.01	0.00	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.04	0.01
Cr_2O_3	0.20	0.16	0.09	0.23	0.14	0.09	0.10	0.15	0.21	0.07	0.06	0.77	0.05	0.19	0.09	0.21	0.20	0.17
Nb_2O_3	0.25	0.38	0.22	0.05	0.44	0.05	0.15	0.17	0.32	0.03	0.20	0.50	0.09	0.44	0.35	0.24	0.11	0.27
Ta_2O_5	0.03	0.05	0.04	0.05	0.03	0.01	0.00	0.06	0.03	0.05	0.04	0.14	0.05	0.04	0.01	0.02	0.06	0.07
P_2O_5	0.01	0.03	0.02	0.05	0.03	0.00	0.00	0.01	0.02	0.01	0.02	0.03	0.00	0.01	0.02	0.00	0.03	0.01
Total	99.24	100.27	99.42	99.6	99.36	100.16	99.38	99.55	99.7	99.13	99.85	99.88	99.34	99.26	100.3	99.54	98.75	99.51
Structural formulae normalized to 4 oxygens																		
Si	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
Al	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
Ti	1.99	1.99	1.99	1.99	1.98	1.99	1.99	1.99	1.99	2.00	1.99	1.97	1.99	1.99	1.99	1.99	1.99	1.99
Fe	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Mn	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
Mg	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
Ca	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
Na	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
K	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
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Nb	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
Ta	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
P	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
Total	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.01	2.00	2.00	2.00	2.00	2.00	2.00

Sample no.	8B1 (light yellow sands)						12B (yellow sands)					
Grain no.	LY1	LY2	LY3	LY4	LY5	LY6	YS1	YS2	YS3	YS4	YS5	YS6
SiO_2	0.00	0.02	0.01	0.04	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.01
TiO_2	98.46	98.13	98.88	98.35	97.68	97.77	98.31	98.32	99.12	98.37	98.09	98.92
Al_2O_3	0.01	0.02	0.01	0.04	0.02	0.00	0.05	0.01	0.01	0.02	0.00	0.01
FeO	0.09	0.08	0.07	0.09	0.15	0.10	0.19	0.03	0.12	0.07	0.08	0.09
MnO	0.00	0.01	0.04	0.00	0.04	0.00	0.02	0.01	0.03	0.03	0.00	0.05
MgO	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.00	0.01
CaO	0.00	0.01	0.00	0.01	0.01	0.05	0.02	0.00	0.01	0.01	0.03	0.01
Na_2O	0.03	0.03	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.01	0.01
K_2O	0.00	0.01	0.02	0.02	0.01	0.01	0.04	0.02	0.01	0.02	0.05	0.00
Cr_2O_3	0.32	0.39	0.07	0.06	0.21	0.23	0.20	0.23	0.22	0.06	0.90	0.14

Table 1 continued

Sample no.	8B1 (light yellow sands)						12B (yellow sands)					
Grain no.	LY1	LY2	LY3	LY4	LY5	LY6	YS1	YS2	YS3	YS4	YS5	YS6
Nb_2O_3	0.20	0.21	0.01	0.12	0.53	0.30	0.61	0.01	0.00	0.03	0.30	0.30
Ta_2O_5	0.02	0.01	0.01	0.04	0.07	0.01	0.05	0.04	0.01	0.01	0.05	0.01
P_2O_5	0.01	0.00	0.00	0.01	0.04	0.00	0.03	0.03	0.01	0.02	0.02	0.01
Total	99.15	98.92	99.13	98.79	98.77	98.48	99.54	98.72	99.58	98.7	99.57	99.57
Structural formulae normalized to 4 oxygens												
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	1.99	1.99	2.00	1.99	1.98	1.99	1.98	1.99	1.99	1.99	1.98	1.99
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Nb	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Ta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.01	2.00

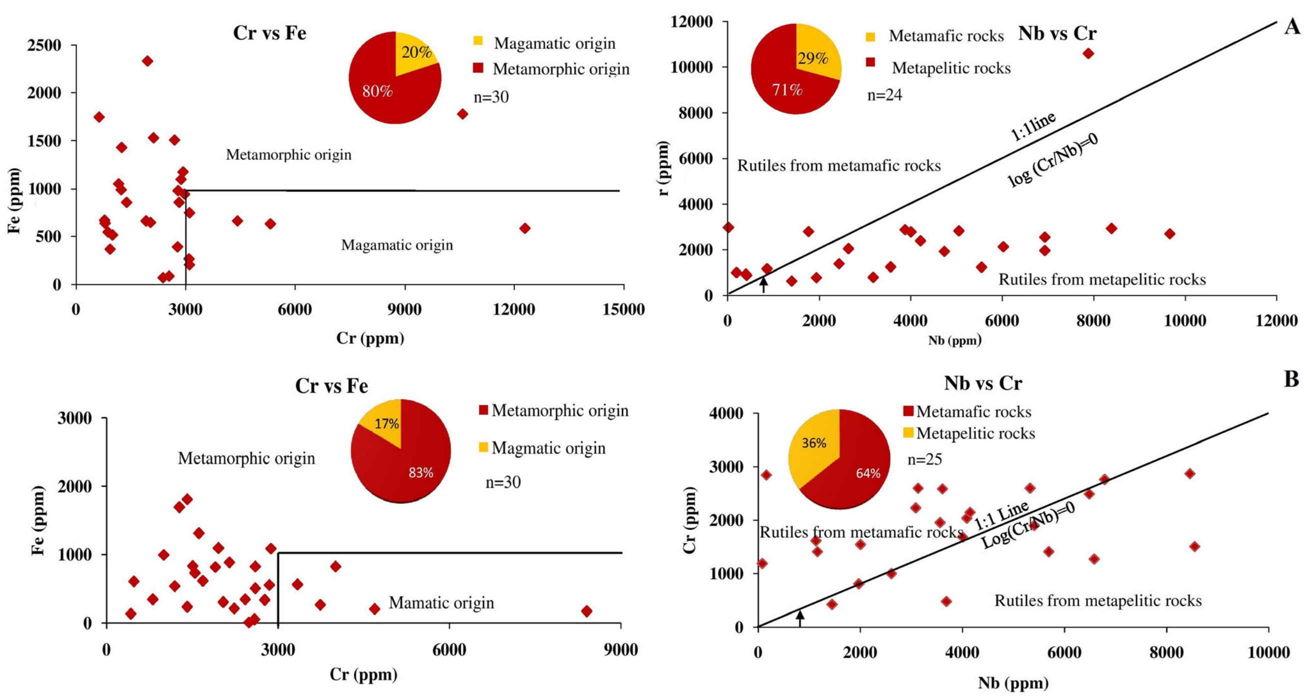

Fig. 2 Scatter plots of Cr versus Fe (Zack et al. [8, 9]) and Nb versus Cr (after Triebold et al. [21]) contents of rutiles. **a** Red sediments and **b** modern coastal sands of Bhimunipatnam–Konada coast

Al and Mg behavior in rutile has been used to discriminate those derived from crustal and mantle origin [10]. The Al and Mg scatter diagrams (Fig. 3a, b) show that most of the rutiles are from crustal rocks.

- Rutiles with Cr content less than 3000 ppm and Cr versus Fe scatter plot suggest that they are derived from metamorphic rocks with an insignificant contribution from magmatic rocks.

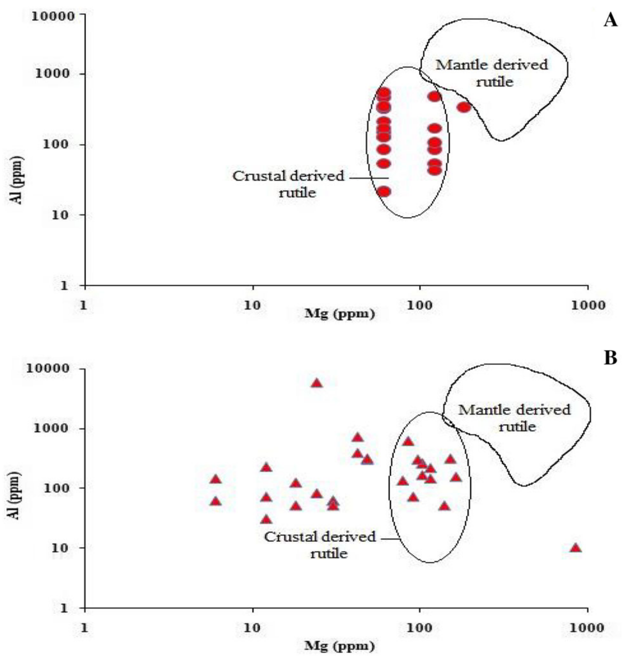

Fig. 3 Scatter plots of Mg versus Al contents of rutiles from **a** red sediments and **b** modern coastal sands of Bhimunipatnam–Konada

- Nb versus Cr scatter plots for rutiles suggest that they are derived mainly from metapelitic rocks in the study area.
- The Al and Mg behavior in rutile from red sediments and modern sands of Bhimunipatnam–Konada coast shows that most of the rutiles are derived from crustal rocks.
- The geochemical behavior of rutile from red sediments and modern sands of Bhimunipatnam–Konada coast indicates that the provenances of rutile for both are unique.

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