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ORIGINAL ARTICLE

Geochemistry of heavy minerals from Uttara Kannada beach sediments, West Coast of India: an insight into provenance studies

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Abstract

Single-grain geochemistry of heavy minerals and its assemblage from beach sediments of Uttara Kannada coast, India, were studied to understand the provenance. The studied heavy minerals were identified under binocular microscope followed by electron probe micro analysis emphasising on spinel, rutile, tourmaline, ilmenite and zircon. Geochemistry of spinel from northern (Rabindranath Tagore) and central (Gokarna) zones suggests their island-arc volcanic origin, particularly peridotites implying the presence of ultramafic suite in the catchment area of Kali and Gangavali rivers. Tourmalines in Devbhag beach from the northern zone are schorl type confirming granitoids as their source rock, while from Rabindranath Tagore beach are dravite type suggesting their metamorphic origin. Conversely, central zone tourmalines are both schorl and dravite type exhibiting dual origin. Rutile geochemistry from northern zone depicts its derivation from metamorphic source. Heavy mineral assemblage of kyanite/sillimanite, rutile, zircon, garnet and staurolite in the southern zone indicates its origin from metamorphic sources. However, the absence of high-grade metamorphic rocks in catchment area of river Sharavati precludes the derivation of garnet and staurolite from this source. Therefore, the presence of such minerals in southern zone may have been brought from further south by northerly alongshore drift where high-grade metamorphic rocks are dominant. Minor heavies-hematite, V-hematite, magnetite, Ti-magnetite, V-magnetite, Ti–V-magnetite present in all three zones reflect their origin from iron ore bodies in the hinterland. From the geological map of Uttara Kannada district, an apparent correlation between hinterland lithology and occurrences of heavy minerals in beach sediments is observed which indicates their derivation from igneous and low-grade metamorphic suites, high-grade metamorphic minerals like garnet and staurolite suggest their derivation from outside. Despite the present work having been carried out in one particular area, the results presented and discussed in this article have wide applicability. The knowledge of sediment input from different sources (river, offshore or alongshore) and transport pathways which play a significant role in making up the composition of beach sands are useful for exploration and/or coastal management studies.

Keywords Heavy minerals · Geochemistry · Provenance · Uttara Kannada coast · West Coast of India · EPMA

1 Introduction

Adequate knowledge of mineral assemblages and geochemical studies of heavy minerals in the beach sediments has always provided an insight into trace their provenance. However, the mineral composition in beach sediments vary morphologically and chemically from the host rocks due to the various geological and geochemical processes concentrating specific minerals mainly due to their density differences (Morton & Hallsworth, 1999). Modal analysis of heavy minerals supports in delineating provenance of the sediments. Some of the stable heavy minerals such as zircons, rutile, tourmalines, garnet, etc., are quite resistant to weathering and, therefore, the chemical composition of such minerals have the potential to serve as indices for provenance analysis (Shimizu et al., 2019). Several studies based on the chemical composition of heavy minerals have been taken up from different parts of the world to understand their provenance (Hanamgond et al., 1999; Kamenetsky et al., 2001; Oszczypko & Salata, 2005; Hegde et al., 2006;

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Bernstein et al., 2008; Nayak et al., 2012; Kowal-Lonka & Stawikkowski, 2013; Bhatta & Ghosh, 2014; Perumalsamy et al., 2016; Dill & Skoda, 2017; Shimizu et al., 2019; Naidu et al., 2019; Shalini et al., 2020; Rai et al., 2020 and references therein).

Heavy minerals such as rutile, spinel, tourmaline, ilmenite, zircons and other assemblages were extensively studied from both west and east coast of India to know their economic viability and understand their distribution pattern along with the provenance. Recently, Naidu et al. (2019) have studied the detrital rutile chemistry from the Bhimunipatnam–Konada coast. Their study revealed that rutiles were derived from metapelitic rocks, primarily khondalites and leptynites occurring in the Eastern Ghats Granulite Belt (EGGB) with a minor contribution from other lithotypes viz., magmatic charnockites, pegmatites and granites. The studies on spinel chemistry, especially chromian spinels have been used extensively to decipher the source rock characteristics (Arai et al., 2006; Bhatta & Ghosh, 2014; Kamenetsky et al., 2001). Bhatta and Ghosh (2014) studied the chromian spinel chemistry from the black sands of Andaman island shoreline and concluded their derivation from various types of peridotites and volcanics belonging to the Andaman ophiolite suite which are exposed in close vicinity. The heavy mineral chemistry of ilmenite, hematite, leucoxene, magnetite, monazite and sillimanite from Ganjam coast, Odissa (Acharya et al., 2009) revealed that these minerals were derived from litho-units of the Precambrian Eastern Ghats Mobile Belt, which primarily consist of khondalite, charnockite, calc-silicate granulite and gneiss. The integrated study on morphology, mineralogy and chemistry of ilmenites and pyriboles from Chavakkad–Ponnani area along the northern Kerala coast (Nayak et al., 2012) suggested that these heavy minerals were derived from amphibolites, granitic gneisses and basic igneous rocks occuring in the hinterland towards the eastern border of Kerala. The heavy mineral assemblage and mineral chemistry of ilmenite and rutile from the Mulki beach, southern coast of Karnataka, revealed that ilmenites were derived from mafic and acidic source rocks while, the rutiles indicated the high-grade metamorphic source (Shalini et al., 2020).

Chavadi and Nayak (1990) and Hanamgond et al. (1999) reported the modal composition of heavy minerals in the beach sands of Uttara Kannada coast and inferred a mixed provenance, while Hegde et al. (2006, 2017) based on the heavy mineral assemblage and ilmenite chemistry arrived similar inferences. Therefore, in such case of multiple sources of the sediments, the single-grain analysis which is also called varietal study of heavy minerals, is crucial to identify the lithology of source rocks and transport pathways. In the last few decades, development in provenance studies based on heavy mineral chemistry have brought advancement in understanding the mineral chemistry and there by providing the specific sources of these heavy minerals. However, such studies related to geochemistry of heavy minerals from Uttara Kannada coast with reference to the provenance are scarce. Hence, the present study focuses on tracing potential sediment sources of the sands of Uttara Kannada coast using single-grain analysis of heavy minerals mainly of detrital spinels, rutiles, tourmalines and ilmenites based on morphologic and petrographic characteristics followed by Electron Probe Micro-Analysis (EPMA).

2 Study area and geology

The study area stretching for about 80 km (latitude 14° 50′ 57.15″–14° 13′ 48.010″ N and longitude 74° 6′ 41.868″–74° 26′ 33.828″ E) falls within the coastal land of Uttara Kannada district, Karnataka, West Coast of India (Fig. 1). Major rivers flowing in the study area are Kali, Gangavali, Aghnashini and Sharavati. These rivers originate in the Western Ghats hill ranges which carry huge sediments and debouch into the Arabian Sea at Karwar, Ankola, Kumta and Honnavara talukas of Uttara Kannada district, respectively (Fig. 1). The study area experiences tropical climate, high humidity, intense chemical weathering, high drainage density and steep slope accompanied by high precipitation which favours the transportation of sediments along with heavy minerals to the coast. The coastal stretch is characterised by geomorphologic features like long open beaches, sheltered beaches, pocket beaches, creeks and spits of different types (Hegde et al., 2012, 2015), generated by the, dynamic coastal and geological processes (Hegde et al., 2021). Sediment movement along the west coast of India shows northward transport by the alongshore current (Kunte & Wagle, 1991; Hegde et al., 2009; Dora & Johnson, 2014; Koti et al., 2015).

The whole Uttara Kannada district is dominated by Archeans rocks consisting of metamorphosed older group of sediments and igneous intrusives along with a younger group of plutonic intrusives termed as peninsular gneiss. The major rock units constitute the metagreywackes, migmatites and associated granitoids with minor metabasalts, ultramafics and carbonates. The Archean granites and gneisses are capped by laterite of about 100ft thickness on flat topped ridges and bluffs along the southern coast. These laterites occasionally show local enrichment of iron and manganese ore. The mineral map overlapped with the geology of the study area consisting iron, manganese, pyrite–chalcopyrite–nickel, titaniferous magnetite, ilmenite, clay and bauxite ores deposits in addition to the above mentioned rocks (Fig. 2).

The study area is divided into three zones, northern, central and southern zone. The northern zone comprises of two estuarine beaches, i.e., Devbhag (DB) in the north

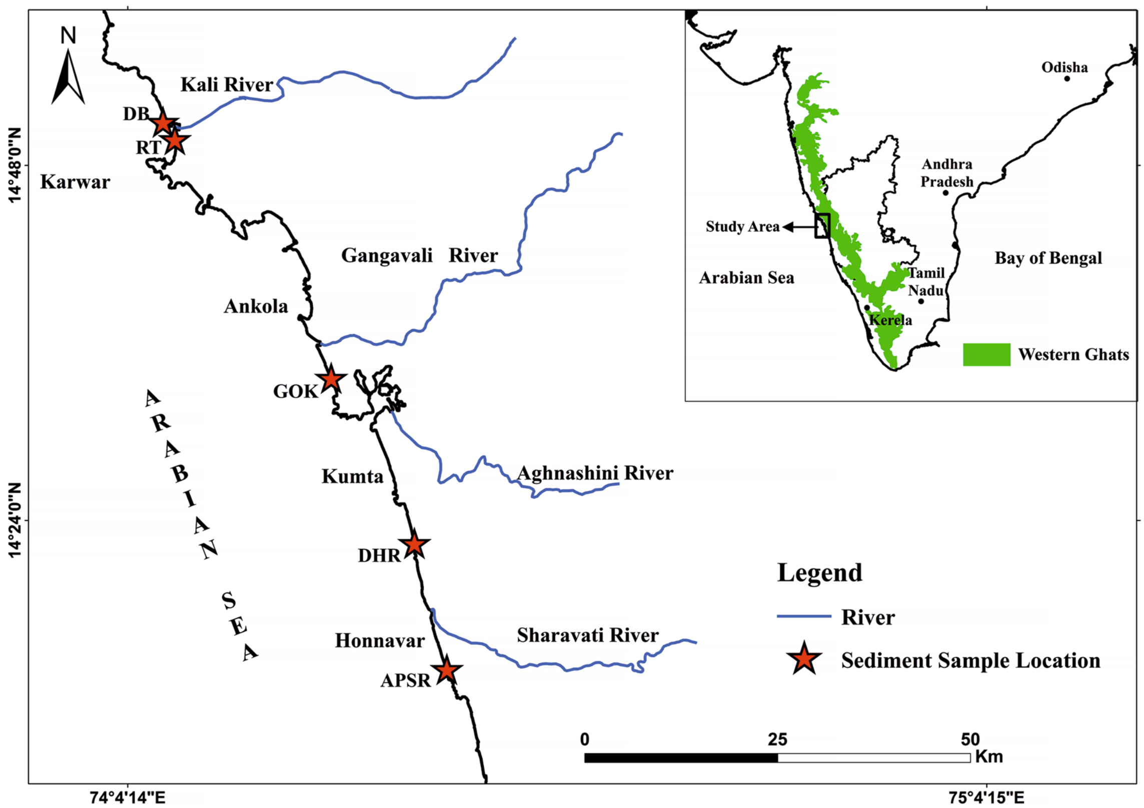

Fig. 1 Map of the study area showing sample locations and major drainage system

and Rabindranath Tagore (RT) in the south of Kali estuary. Central zone consits of Gokarna (GOK) beach which is bounded by Gangavali river in the north and Aghnashini river in the south. The southern zone consists of Dhareshwar (DHR) and Apsarakonda (APSR) beaches. Dhareshwar beach is bounded by a small river in the north and Sharavati river in the south while the Apsarakonda beach is bounded by Sharavati river in the north and a small ephemeral stream along with adjoining headland in the south.

3 Materials and methods

Five foreshore sediment samples from Devbhag (DB; 14° 50′ 57.16″ N; 74° 6′ 41.87″ E), Rabindranath Tagore (RT; 14° 49′ 46.74″ N; 74° 7′ 31.3″ E), Gokarna (GOK; 14° 33′ 38.74″ N; 74° 18′ 26.93″ E), Dhareshwar (DHR; 14° 22′ 27.98″ N; 74° 24′ 15.98″ E) and Apsarakonda (APSR; 14° 13′ 56.39″ N; 74° 26′ 31.92″ E) beaches, were collected using the plastic core liner of 4 cm diameter and driving it to 8 cm depth. The collected samples were water washed and dried and representative proportions were obtained by coning and quartering and were treated chemically to remove carbonate materials, iron coating and organic contents (Ingram, 1970). The treated samples were dried and subjected for sieve analysis at ¼ phi intervals using ASTM sieves on Ro-top sieve shaker. The size fractions ranging between 0.125 and 0.090 mm were chosen for further analysis. This size range is suitable for fine-grained and well-sorted sediments as it allows uniform observing conditions and reduces the impact of hydraulic sorting (Morton, 1985; Mange & Maurer, 1992). Further, these fractions were subjected for magnetite separation using bar magnet and the non-magnetic fractions were subjected to heavy liquid separation using Bromoform. For petro-mineralogical study, a set of 200–300 grains were identified and point counted using binocular microscope. The number percentage of minerals were established and represented in Fig. 3. The selected heavies were then chosen for single-grain analysis using a CAMECA-SX-100 Electron Probe Micro Analyser at Geological Survey of India, NCEGR, Bengaluru, India. Accelerating voltage of 15 keV and 40 nA beam current were used during the analysis with the probe spot being approximately 0.5 µm.

4 Results

4.1 Heavy mineral assamblages

The study includes heavy mineral assamblages and relative abundance in three zones viz., northern, central and southern

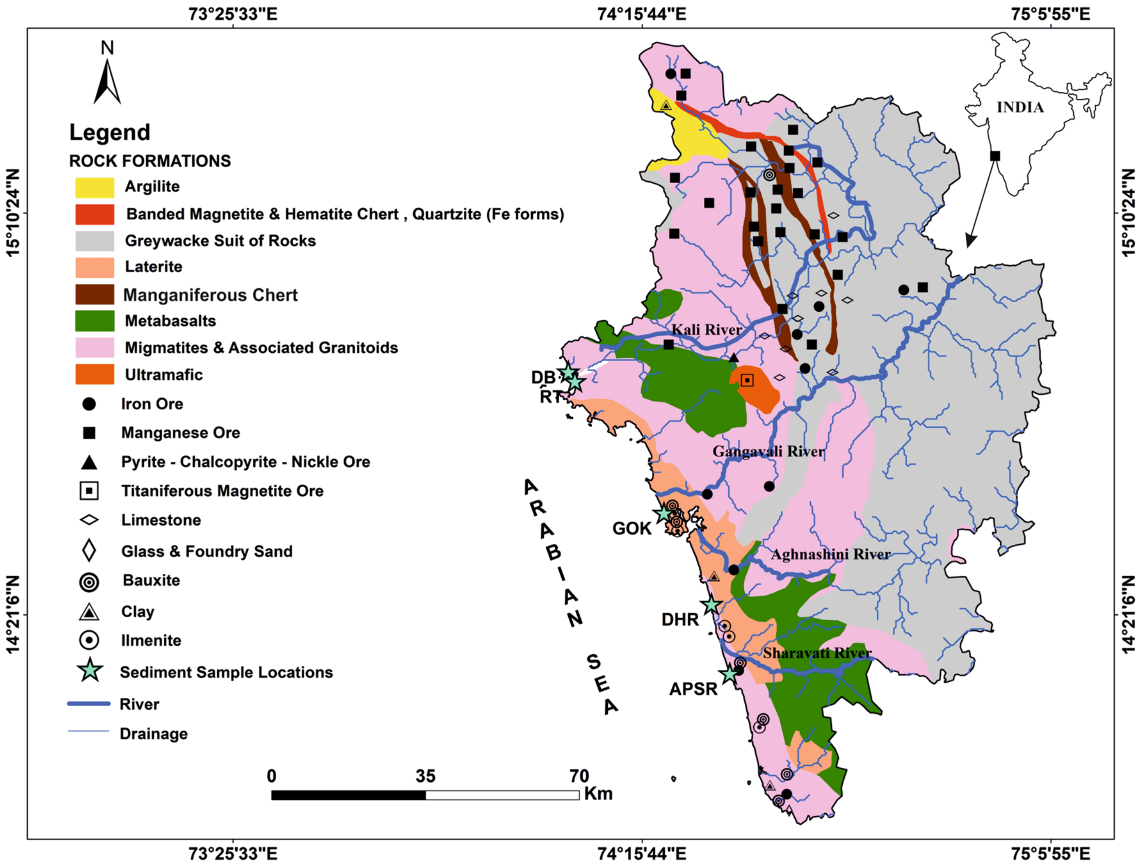

Fig. 2 Simplified geological map of Uttara Kannada district (after, Geological survey of India, 1983), overlapped with drainage system

zone of Uttara Kannada coast. The heavy minerals identified during point counting and those through EPMA analysis are atmost same. The individual heavy mineral percentage are represented in Fig. 3 and heavy minerals identified through EPMA are presented in Table 1.

1. Petrographic studies for heavy minerals from the northern zone viz., Devbagh and Rabindranath Tagore beach indicated the presence of opaques (ilmenite and iron oxides), epidote, amphibole, kyanite/sillimnite, zircon, pyroxene, spinel, tourmaline, rutile and garnet (Table 1). The percentage of heavy mineral abundances of both the beaches obtained from point-counting method is represented in Fig. 3a, b. The ZTR index for Devbhag and Rabindranath Tagore beach is 7.47% and 11.52%, respectively.
2. Gokarna beach from the central zone comprised of opaques, amphibole, zircon, tourmaline, epidote, rutile, spinel, pyroxene and garnet (Table 1) in decreasing order of abundance (Fig. 3c) with ZTR index being 16.52%.
3. In southern zone, the Dhareshwar beach indicated the presence of opaques, amphibole, epidote and garnet (Table 1); and the Apsarakonda beach comprised of opaques, epidote, kyanite/sillimnite, amphibole, rutile and zircon (Table 1) in order of decreasing abundances (Fig. 3d, e). The ZTR index estimated for the Dhareshwar beach and Apsarakonda beach are 2.2 and 9.58%, respectively.

4.2 Micromorphological features of selected heavy minerals

4.2.1 Zircon

Micromorphological studies of zircon population shows that the grains are multicolour, the degree of roundness range from subhedral to euhedral and from angular to rounded indicating zircons of short-as well as long-distance transportation and/or reworking of the relict sediments by wave processes (Fig. 4a).

4.2.2 Tourmaline

The tourmaline population in the study area are euhedral (elongated prism) (Fig. 4b) indicating, short distance transportation or its derivation from primary source rocks.

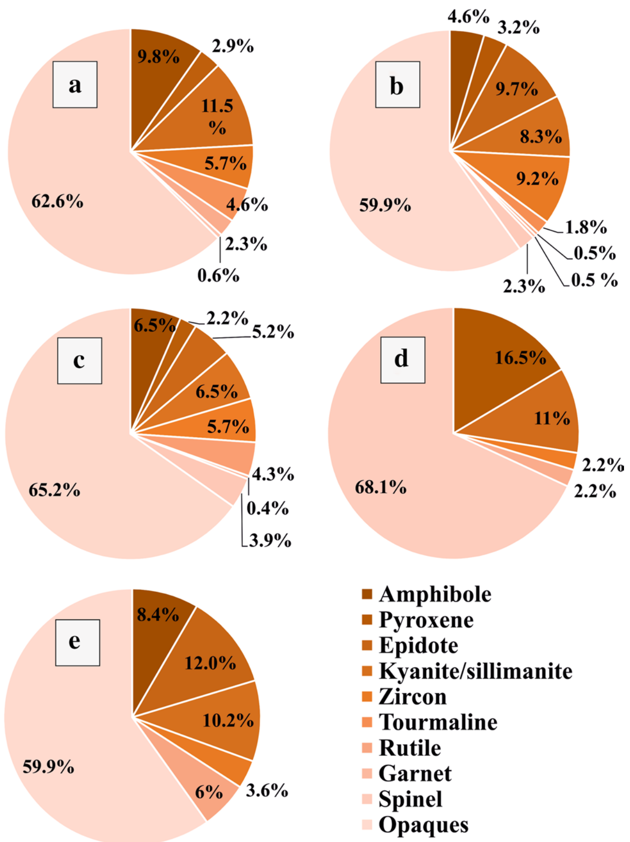

Fig. 3 Heavy mineral abundance in the beach sediments of Uttara Kannada coast: **a** Devbhag beach, **b** Rabindranath Tagore beach, **c** Gokarna beach, **d** Dhareshwar beach, **e** Apsarakonda beach

4.2.3 Ilmenite

Ilmenites of the study area are characterised by the presence of corrosion pits, re-entrants, etch pits and grooves indicating progressive weathering textures. These ilmenites can be broadly classified into two types, angular ilmenites probably of younger generation (Fig. 4c), while second type are the altered ones, sub-rounded to rounded (Fig. 4d), that indicates reworking by wave processes.

4.3 Heavy mineral composition

The heavy mineral composition obtained from EPMA analysis are focused for interpreting provenance considering mainly spinel, rutile, tourmaline and ilmenite.

4.3.1 Spinel

The spinels are observed from northern (Rabindranath Tagore) and central (Gokarna) zones. The chromium content in these spinels (38.02–64.52%) shows significantly higher concentrations and are, therefore, considered as chromian spinels (Table 2). TiO_2 and Al_2O_3 contents vary between 0.37–4.29% and 4.14–27.43%, respectively. These elemental oxides are significant to distinguish between spinels crystallised from magmas in distinct geodynamic environment such as Mid Oceanic Ridge Basalt (MORB) and island-arc volcanics (Bhatta & Ghosh, 2014). Based on the tectonic discrimination diagram given by Kamenetsky et al., (2001) (Fig. 5a), it is observed that almost all the studied grains occupy the field of volcanic spinels, except 1 grain from Rabindranath Tagore beach (Kar 19/1) which shows affinity towards MORB type peridotite. Another plot using the same elemental oxides (after, Kamenetsky et al., 2001) reveals that most of the analysed spinels from Rabindranath Tagore and Gokarna beaches cluster in island-arc field, except the two grains (Kar 15/1 and 19/1) which plot in MORB field and one (Kar 16/1), outside the field (Fig. 5b). The Cr/(Cr + Al) ratio of spinel for island-arc peridotites ranges from 0.1 to 0.8 while for MORB peridotites it is < 0.6 (Arai et al., 2006). In the present study, the chromian spinel exhibit Cr/(Cr + Al) ratio ranging from 0.6 to 0.9, which suggests its derivation from the island-arc peridotites (Table 2).

Table 1 Heavy minerals assemblage in Uttara Kannada coastal sediments identified using EPMA

Location	DB	RT	GOK	DHR	APSR
Amphibole	*	*	*	*	*
Clinopyroxene	*	*	*		
Orthopyroxene	*	*	*		
Epidote	*	*	*	*	*
Kyanite/sillimanite	*	*			*
Hematite	*	*	*		
V-Hematite			*		
Magnetite		*			
Ti-magnetite		*			
V-magnetite			*		
Ti–V-magnetite				*	
Ilmenite	*	*	*	*	*
Titanite	*				
Rutile		*	*		*
Spinel		*	*		
Tourmaline	*	*	*		
Zircon	*	*	*		*
Garnet				*	
Staurolite					*

*Indicates the presence of heavy minerals

4.3.2 Rutile

Rutile is found in northern (Rabindranath Tagore), central (Gokarna) and southern (Apsarakonda) zone beach

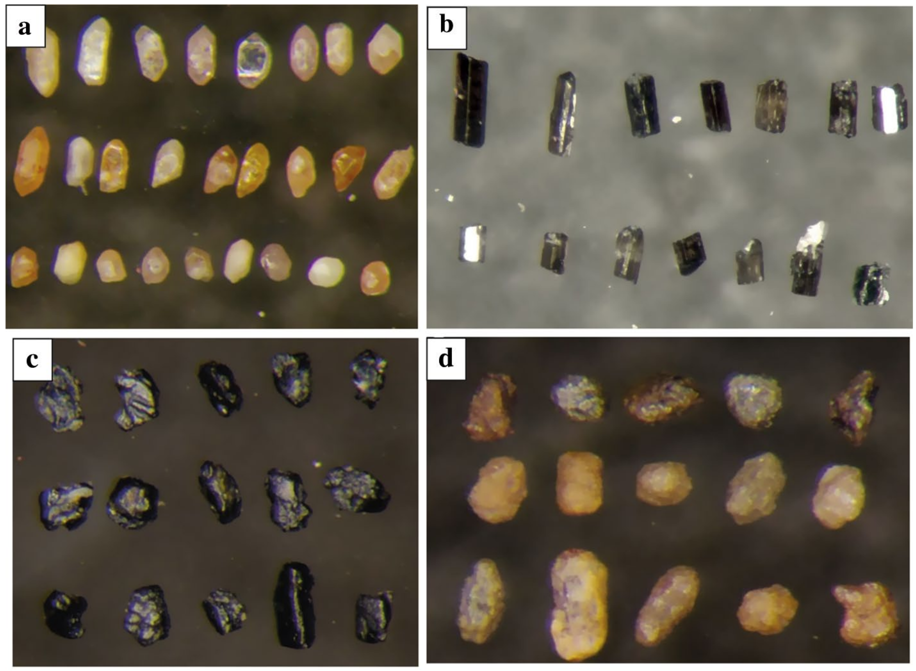

Fig. 4 **a** Zircon, **b** Tourmaline, **c** Ilmenite, **d** Altered ilmenite under binocular microscope

Table 2 Chemical composition of *spinels* from the sediments of Uttara Kannada coast

Location	RT						GOK	
Composition	9/1	12/1	15/1	16/1	17/1	19/1	8/1	9/1
SiO_2	0.07	0.04	0.05	0.08	0.05	0.13	0	0.07
TiO_2	0.50	0.53	0.44	4.29	0.76	0.42	0.37	0.48
Al_2O_3	4.14	6.96	16.82	10.18	8.12	27.43	9.18	8.46
FeO	34.24	33.45	28.24	33.08	16.02	22.58	17.92	24.01
MnO	2.04	2.05	0.33	0.34	0.31	0.24	0.22	0.34
MgO	0.28	1.8	8.09	7.66	14.23	12.47	9.52	5.71
CaO	0	0.03	0	0.02	0	0.01	0	0
Na_2O	0.04	0.03	0.02	0.04	0	0	0	0
K_2O	0	0.01	0.03	0.02	0	0	0	0.03
BaO	0	0	0	0	0	0	0	0.02
NiO	0.23	0.1	0.23	0.09	0	0.12	0.01	0.05
V_2O_3	0.11	0.04	0.1	0.7	0.03	0.03	0.02	0.1
Cr_2O_3	57.9	53.69	47.41	42.64	61.27	38.02	64.52	60.86
ZrO_2	0	0	0	0	0	0	0	0
P_2O_5	0	0.02	0.02	0.01	0.01	0.05	0.07	0.03
Total	99.55	98.75	101.78	99.15	100.8	101.5	101.83	100.16
Cr/(Cr + Al)	0.95	0.91	0.78	0.84	0.91	0.64	0.90	0.90

sand samples. TiO_2 content of the rutiles of northern zone ranges from 95.76 to 99.13%, central zone 98.37–100% and southern zone it is 96.54–98.52%. The Fe content ranges from 3775.8 to 10,967.8 ppm in northern zone, 269.7–4584.9 ppm in central zone and 2247.5–9439.5 ppm in southern zone. The Cr content in the beach sediments of northern, central and southern zone, respectively, varies between 0 and 1368 ppm, 68.4–1368 ppm and 0–136.8 ppm (Table 3). Rutiles with Fe content < 1000 ppm and Cr content > 3000 ppm is considered to be derived from magmatic origin (Naidu et al., 2019; Zack et al., 2004), but the analysed rutiles have Fe content > 1000 ppm (except 1 grain, i.e., GOK 12/1) and Cr content < 3000 ppm which indicates their non-magmatic nature (Table 3). In the Cr versus Fe plot given by Zack et al. (2004), all the analysed rutiles cluster in the field of metamorphic origin confirming their non-magmatic nature (Fig. 6).

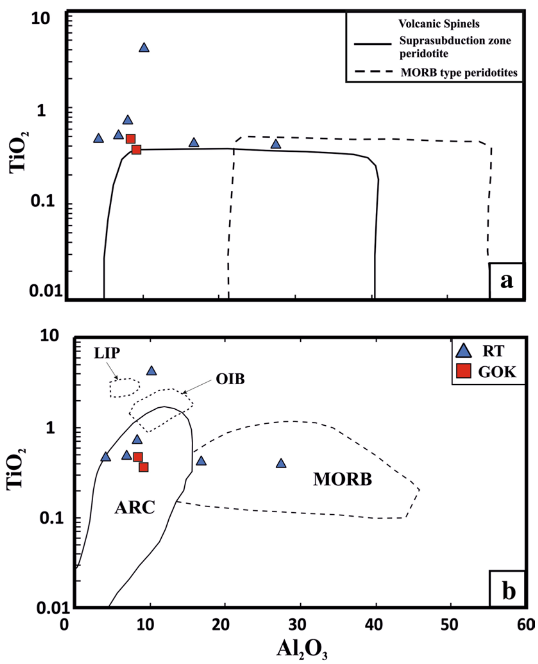

Fig. 5 **a** and **b** Al_2O_3 vs. TiO_2 compositional diagrams of spinels (after, Kamenetsky et al., 2001). Mid-oceaanic ridge basalt (MORB), oceanic-island basalt (OIB), large igneous province (LIP) and island-arc magmas (ARC). Symbols are the same as in (**b**)

4.3.3 Tourmaline

The tourmalines are found in northern (Devbhag and Rabindranath Tagore) and central zones (Gokarna). The main elements in analysed tourmalines are Si, Al, Fe, Mg and Na. From the Mg–Al–Fe trilinear plot (after, Henry & Guidotti, 1985) it is clear that all the tourmalines belong to the schorl (Fe-end member)–dravite (Mg-end member) series (Fig. 7). Most of the tourmalines fall in the 6th field, which represents Fe^{+3}-rich quartz–tourmaline rocks, calc-silicate rocks and metapelites with a few being on the transitional line between 3rd and 6th field, where the 3rd field represents Fe^{+3}-rich quartz–tourmaline rocks (hydrothermally altered granites). $Mg/(Mg+Fe_{tot})$ ratio overall shows greater and lesser values than 0.40 which indicates the presence of both schorl and dravite types of tourmalines, respectively (Henry & Dutrov, 1992, 1996) (Table 4). The schorl type tourmalines are essentially found in Devbhag beach whereas the dravite types ones are in Rabindranath Tagore beach sediments of northern zone. The central zone consists of both dravite and schorl type of tourmalines. Overall, it is noticed that the schorl type tourmalines are dominant than those of dravite type.

4.3.4 Ilmenite

Ilmenite is the common mineral found in all samples of the study area. TiO_2 content of the ilmenites in northern zone (Devbhag and Rabindranath Tagore) ranges from 45.86 to

Table 3 Chemical composition of *rutiles* from the sediments of Uttara Kannada coast

Location	RT		GOK					APSR			
Composition	18/1	20/1	11/1	12/1	13/1	14/1	15/1	8/1	10/1	11/1	27/1
SiO_2	0	0.03	0.08	0	0.16	0.15	0.24	0.01	0	0.05	0.06
TiO_2	99.13	95.76	100.14	99.95	100.07	99.64	98.37	98.52	96.54	98.05	97.17
Al_2O_3	0.02	0	0.01	0	0.03	0.03	0.05	0	0	0.04	0.01
FeO	0.42	1.22	0.17	0.03	0.22	0.28	0.51	0.25	1.05	0.39	0.28
MnO	0	0.01	0	0.04	0	0.06	0.06	0.07	0.13	0	0
MgO	0	0	0	0.01	0.01	0	0	0	0.03	0.03	0.01
CaO	0.01	0	0.05	0.01	0.05	0.05	0.06	0.08	0.04	0.05	0.02
Na_2O	0.02	0.02	0	0.03	0.01	0.03	0	0.04	0.01	0.04	0.01
K_2O	0	0.01	0.01	0.01	0.05	0.03	0	0.01	0.03	0	0.01
BaO	0	0	0	0	0.04	0.2	0	0	0	0	0.03
NiO	0	0	0	0.02	0.01	0.08	0.03	0.08	0.04	0.04	0
V_2O_3	0	0.49	0	0.31	0	0	0	0	0	0	0
Cr_2O_3	0.2	0	0.02	0.2	0.04	0.01	0.02	0.02	0	0.01	0.01
ZrO_2	0.31	0	0	0	0.08	0.03	0	0.08	0	0	0.2
P_2O_5	0.02	0	0.08	0.02	0.01	0.01	0.01	0.03	0.03	0	0
Total	100.13	97.54	100.56	100.63	100.78	100.6	99.35	99.19	97.9	98.7	97.81
Fe (ppm)	3775.8	10,967.8	1528.3	269.7	1977.8	2517.2	4584.9	2247.5	9439.5	3506.1	2517.2
Cr (ppm)	1368	0	136.8	1368	273.6	68.4	136.8	136.8	0	68.4	68.4

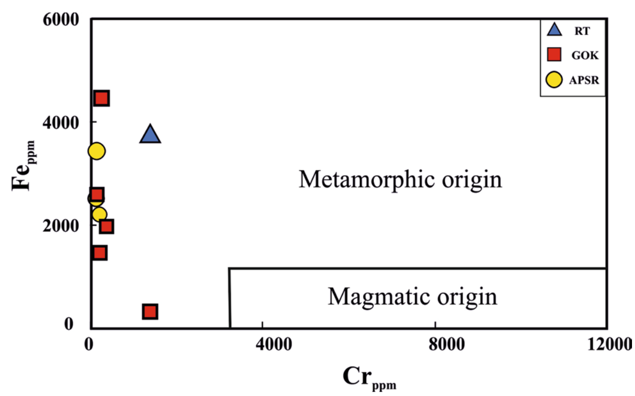

Fig. 6 Scatter plots of Cr versus Fe (after, Zack et al., 2004)

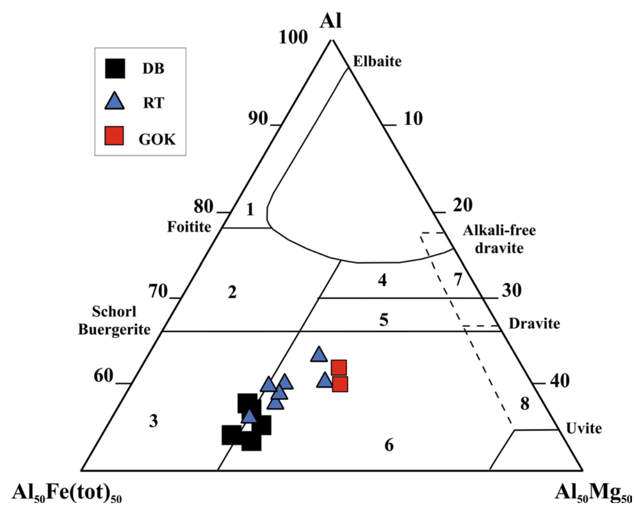

Fig. 7 Provenance of tourmalines from Al–$Fe_{(tot)}$–Mg diagram (numbering of fields as in the triangle: (1) Li-rich granitoid, pegmatites and aplites, (2) Li-poor granitoids and associated pegmatites and aplites, (3) Fe^{3+}-rich quartz–tourmaline rocks (hydrothermally altered granites), (4) Metapelites and metapsammites coexisting with an Al-saturating phase, (5) Metapelites and metapsammites not coexisting with an Al-saturating phase, (6) Fe^{3+}-rich quartz–tourmaline rocks, calc-silicate rocks and metapelites, (7) Low-Ca metaultramafics and Cr, V-rich metasediments, (8) Metacarbonates and meta-pyroxenites (after, Henry & Guidorn, 1985)

66.54%; FeO, 21.56–52.19% and MnO, 0.45–3.71%. TiO_2 content in ilmenite of central zone (Gokarna) is 49.24%; FeO, 47.31% and MnO, 1.3%, whereas in southern zone (Dhareshwar and Apsarakonda) TiO_2 ranges from 50.59 to 66.98%; FeO from 14.38 to 47.53% and MnO varying from 0.0 to 3.57%. Most of the studied ilmenites are devoid of Cr_2O_3 ($Cr_2O_3 = 0.0$) except the three grains from northern zone which have < 1% (Table 5).

The Mn/Mg ratios obtained from ilmenites of the study area shows 0.14–132.21, 2.88 and 0.0–198.96 in northern, central and southern zones, respectively. The ilmenites with high Mn/Mg ratio are indicative of fresh ilmenites (unaltered), whereas the low ratio represents altered ilmenites in the beach sands (Table 5). Ilmenites from the northern zone exhibit Ti/(Ti + Fe) ratios ranging from 0.37 to 0.67, in central zone is 0.41 and in southern zone it varies from 0.42 to 0.76. Lower and higher values of Ti/(Ti + Fe) ratio corroborate the presence of both fresh (unaltered) and altered ilmenites, respectively (c.f. Mallik et al., 1987; Shalini et al., 2020 and references therein).

Ni, Cr and V contents of ilmenites from northern zone (Devbhag and Rabindranath Tagore beaches) range from 0.0 to 666.9 ppm, 0–3898 ppm and 0.0–0.0679 ppm, respectively (Table 5). The Cr content from central zone (Gokarna) ilmenite is 342 ppm with no Ni and V. In the southern zone ilmenites (Dhareshwar and Apsarakonda), Ni and Cr contents range from 0.0 to 963.3 ppm and 0–27838.8 ppm, respectively, with the absence of V.

The Zr content in the northern zone ilmenites ranges from 0.0 to 814 ppm, whereas in both central and southern zone the concentration is 74 ppm. The studied ilmenites are characterised by low values of Zr/Cr ratios (0.0–0.22) except for a few grains found in the northern zone (Rabindranath Tagore beach) and one grain from the southern zone (Dhareshwar beach) which ranges from 0.72 to 2.16 (Table 5).

5 Discussion

The heavy mineral assemblages consist of ultra-stable (zircon, tourmaline, rutile and garnet) to less stable (ilmenite, spinel, titanite, epidote, amphibole, pyroxene) heavy minerals. These are mainly supplied by the rivers flowing through the study area which carries a large part of sediments resulting from the disintegration of source rocks (Chavadi & Nayak, 1990).

The mineral assemblages of opaques, amphibole, pyroxene, rutile, epidote and zircon in the heavy mineral suite of all three zones suggests igneous rock source while the presence of garnet, kyanite/sillimanite, tourmaline, hornblende and zircon suggests the contribution from high-grade metamorphic rocks. Lower ZTR index (2.2–16.52%) suggests that sediments are mineralogically immature (Hubert, 1962) which indicates the predominance of unstable minerals in assemblages implying fresh input of sediments by the rivers.

The morphological features of the studied zircons show euhedral zircon population suggesting their derivation from the erosion of proximal granitoids, which are the major lithotype of the headland and/or offshore islands. The subrounded to rounded zircons suggest that they have undergone recycling and/or long distance of transport or prolonged sorting on the beach and also may have been derived from metasedimentary rocks, especially greywackes which are dominant in the source area. Based on the visual interpretation from our studies, it is indicated that zircon population

Table 4 Chemical composition of *tourmalines* from the sediments of Uttara Kannada coast

Location	DB					RT		GOK						
Composition	23/1	24/1	27/1	37/1	38/1	36/1	37/1	21/1	22/1	24/1	26/1	27/1	29/1	30/1
SiO_2	36.1	36.44	35.78	36.68	36	35.79	35.34	36.59	36.15	36.21	36.25	36.52	35.7	36.61
TiO_2	0.24	0.62	0.45	0.80	0.29	1.01	1.11	0.06	0.20	0.94	0.45	0.21	1.59	0.56
Al_2O_3	31.38	30.31	28.69	29.29	29.41	30.21	30.72	31.89	31.28	29.99	30.39	32.67	29.45	30.96
FeO	9.42	9.25	9.92	9.22	10.53	5.59	5.34	8.33	7.69	9.38	6.05	5.96	7.94	7.94
MnO	0.04	0.03	0	0	0.01	0.07	0.08	0.05	0.07	0.11	0.01	0.05	0.08	0
MgO	6.03	6.21	7.12	7.15	6.16	8.93	8.58	6.38	7.05	6.34	8.34	7.64	6.82	7.02
CaO	0.64	0.25	0.35	0.32	0.57	1.30	1.20	1.03	0.18	0.70	1.46	0.10	0.32	0.10
Na_2O	2.53	2.69	2.77	2.69	2.54	2.42	2.48	1.85	2.71	2.62	2.07	2.23	2.78	2.81
K_2O	0.01	0.03	0.04	0.05	0.04	0	0.04	0.05	0	0.04	0.05	0.03	0.01	0.02
BaO	0	0	0	0	0	0.04	0	0.04	0	0.05	0.06	0	0	0
NiO	0	0.10	0.06	0.04	0	0.12	0.02	0	0.12	0.08	0	0	0	0.01
V_2O_3	0.08	0.05	0.03	0.03	0.39	0.01	0.04	0	0.18	0.11	0.1	0.02	0.02	0.03
Cr_2O_3	0.10	0.10	0.06	0	0.05	0.14	0.23	0.02	0.19	0.05	0.03	0.02	0.23	0.04
ZrO_2	0	0	0.01	0	0.01	0	0.04	0.01	0	0	0.03	0.01	0	0
P_2O_5	0.02	0.05	0.05	0.06	0.01	0.08	0.01	0.05	0.05	0.01	0	0.01	0	0.02
Total	86.59	86.13	85.33	86.33	86.01	85.71	85.23	86.35	85.87	86.63	85.29	85.47	84.94	86.12
$Mg/(Mg+Fe_{tot})$	0.30	0.31	0.32	0.34	0.28	0.52	0.52	0.34	0.38	0.31	0.48	0.46	0.37	0.37

display unweathered stage of weathering, however, the angular zircon grains due to mechanical rupturing cannot be precluded (after, Ando et al., 2012). Similarly, the presence of euhedral tourmalines represents unweathered stage but degree of progressive corrosion represents the initial stage (after, Ando et al., 2012). On the other hand, the ilmenite grains display full suite of weathering stages-unweathered, corroded, etched, deeply etched and skeletal stages (Ando et al., 2012). This could be due to derivation from a variety of weathered sources (Nesbitt et al., 1997), such as bedrock and soil profiles of varied types and maturities, eroded by different processes (e.g., rill to gully erosion, landslides) under varying climatic and geomorphological conditions (e.g., temperature, rainfall, relief, vegetation) (Ando et al., 2012). Thus, from the foregoing account, the identified mineral species clearly reveal that the heavy minerals suite of the Uttara Kannada coast were derived from a mixed provenance of metamorphic, igneous rocks and reworked sediments which corroborates with the earlier studies on beach sands of coastal Karnataka (Chavadi & Nayak, 1990; Hanamgond, 1993; Hanamgond et al., 1999; Hegde et al., 2006, 2017; Shalini et al., 2020).

However, based on mineral chemistry for the studied heavies (spinel, rutile, tourmaline, ilmenite), we reveal their provenance as follows:

5.1 Spinel

In general, the analysed chromian spinels show similarity with respect to chromium content which signifies a common source rock (Bhatta & Ghosh, 2014). The Cr/Cr + Al ratio and Al_2O_3–TiO_2 plots suggest that the studied chromian spinels, particularly in northern (Rabindranath Tagore) and central (Gokarna) zones, are formed in island-arc peridotites (Table 2). This result corroborates with the hinterland geology wherein a large part of the sediments is transported towards the Rabindranath Tagore and Gokarna beaches through two different rivers (Kali and Gangavali river, respectively) with different catchment areas but both flowing through the same ultramafic suite (Fig. 2).

5.2 Rutile

Rutile is one of the important stable minerals in sedimentary environment and, therefore, the rutile chemistry helps to deduce the provenance (Naidu et al., 2019; Shalini et al., 2020). From the geochemistry of rutiles (Fe–Cr contents; Table 3), it is clear that the analysed rutiles from the study area are non-magmatic in nature. This is also confirmed from the Cr versus Fe scatter plot (Fig. 6), which suggests that they were derived from the rocks of metamorphic origin (Naidu et al., 2019; Zack et al., 2004). These results corroborate with hinterland geology, i.e., the presence of metamorphic rocks like metabasalts, migmatites and granitoids are likely source for rutiles (Fig. 2).

5.3 Tourmaline

Geochemically, the studied tourmalines belong to the schorl–dravite series which crystallises in granitoids

Table 5 Chemical composition of *ilmenites* from the sediments of Uttara Kannada coast

Location	DB							RT				GOK	DHR					APSR		
Composition	10/1	11/1	12/1	13/1	25/1	28/1	31/1	10/1	11/1	13/1	14/1	7/1	3/1	4/1	5/1	8/1	18/1	6/1	7/1	9/1
SiO_2	0.08	0.05	0	0.06	0.28	0.01	0.28	0	0.05	0.07	0	0	0.03	0.15	0.01	0.06	0	0.05	0.05	0.38
TiO_2	52.21	50.97	49.78	52.83	49.08	52.47	66.54	45.86	50.77	51.87	51.8	49.24	52.36	50.59	51.72	56.31	50.73	51.78	50.91	66.98
Al_2O_3	0	0	0.14	0.02	0	0.01	1.3	0	0.08	0.03	0.07	0	0	0.11	0	0	0	0.02	0	4.69
FeO	44.57	47.13	46.44	42.55	45.48	47.12	21.56	52.19	46.42	46.07	42.1	47.31	46.6	46.1	45.07	33	47.53	44.42	44.3	14.38
MnO	2.79	1.67	0.56	3.71	1.64	1.03	2.86	1.82	0.58	0.45	0.61	1.3	0.93	3.1	3.57	2.05	0.73	2.48	2.6	0
MgO	0.05	0.05	0.36	0.04	0.34	0.01	0.18	0.2	2.38	0.54	5.46	0.58	0.66	0.02	0.37	0.04	0.53	0.03	0.16	0.08
CaO	0	0	0.06	0.02	0.05	0.04	0.1	0	0.01	0.02	0	0	0.02	0.02	0	0.05	0	0.06	0.09	0.13
Na_2O	0.01	0	0.03	0	0.05	0	0.05	0	0.06	0.06	0.01	0.08	0.02	0.01	0	0.03	0.02	0.01	0.04	0.01
K_2O	0.02	0	0.01	0	0	0.01	0	0.03	0	0	0	0	0.04	0	0.02	0	0.02	0.02	0.01	0
BaO	0.07	0	0	0	0.02	0	0	0	0	0	0	0.06	0	0	0.05	0	0.17	0	0	0
NiO	0	0.03	0.07	0.06	0.02	0.09	0	0.06	0	0	0.09	0	0.06	0.05	0	0	0.13	0.04	0	0.01
V_2O_3	0	300	700	600	200	900	0	600	0	0	900	0	600	500	0	0	1300	400	0	100
Cr_2O_3	0	0	0	0	0	0	0.1	0.03	0.05	0	0	0	0	0	0	0	0	0	0	0
ZrO_2	0	0	0	0	0	0	1000	300	500	0	0	0	0	0	0	0	0	0	0	0
P_2O_5	0.02	0	0	0.03	0.09	0	0.57	0.02	0.03	0.05	0.32	0.05	0.06	0.01	0.02	0.06	0	0	0.01	4.07
Cr (PPM)	200	0	0	300	900	0	5700	200	300	500	3200	500	600	100	200	600	0	0	100	40,700
ZrO_2	0	0	0.11	0	0	0	0	0.04	0.02	0.1	0	0.01	0	0.01	0	0	0	0	0	0
P_2O_5	0	0.04	0	0.03	0.01	0	0.39	0.04	0.02	0.04	0	0	0.05	0	0.04	0.05	0.05	0	0.03	0.63
Total	99.82	99.94	97.56	99.35	97.06	100.79	93.93	100.29	100.47	99.3	100.46	98.63	100.83	100.17	100.87	91.65	99.91	98.91	98.2	91.36
Ti(Ti + Fe)	0.44	0.42	0.42	0.45	0.42	0.43	0.67	0.37	0.42	0.43	0.45	0.41	0.43	0.42	0.43	0.53	0.42	0.44	0.43	0.76
Mn/Mg	71.62	42.87	2.00	119.05	6.19	132.21	20.39	11.68	0.31	1.07	0.14	2.88	1.81	198.96	12.38	65.78	1.77	106.11	20.86	0.00
Zr/Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.16	0.72	2.16	0.00	0.22	0.00	1.08	0.00	0.00	0.00	0.00	0.00	0.00

(schorl type) and metamorphic rocks (dravite type) (Henry &Dutrov, 1992, 1996; Oszczypko & Salata, 2005). However, schorl type tourmalines are dominant in the study area signifying the contribution from the granitoid is comparatively higher than that of metamorphic rocks. These results can be confirmed from $Mg/(Mg+Fe_{tot})$ ratio attributed to the hinterland granitoids and metamorphic rocks (Table 4). The Mg–Al–Fe trilinear plot (Kamenetsky et al., 2001) suggests that most of the studied tourmalines cluster in the field of Fe^{+3}- rich quartz–tourmaline rocks, calc-silicate rocks and metapelites and is correlated with the granitic and migmatitic rocks present in the hinterland (Fig. 2).

5.4 Ilmenite

The low Ti/(Ti + Fe) and high Mn/Mg ratios indicates fresh ilmenites whereas high Ti/(Ti + Fe) and low Mn/Mg ratios suggest the presence of altered ilmenites in the sediments (Table 5). As it is a widespread accessory mineral found in most of the lithotypes, the rocks present in the hinterland of the study area viz., granitic–tonalitic compositions, amphibolites and high-grade metamorphic rocks such as migmatites along with sillimanite–kyanite bearing metasediments are considered as the main source for the studied ilmenites. In ilmenite chemistry, the Ni, Cr and V contents serve as an indicator of source rocks suggesting gneissic to basic provenance (Hegde et al., 2006). The low Zr/Cr ratios of almost all the studied ilmenites suggest gneisses as their parent rocks while few ilmenites with higher ratios may have been derived from the granitoids (major lithotype) present in the catchment area.

By integrating observations from heavy mineral assemblage, geology of catchment area, morphology and geochemistry of heavy minerals, it is inferred that heavy minerals in the beach sediments of all three zones have a mixed mode origin. From the geological map of Uttara Kannada district, an apparent correlation between the hinterland lithology and occurrences of heavy minerals in beach sediments can be observed. The presence of amphiboles, pyroxenes and epidote in northern and central zone beach sediments reflects the mafic to intermediate magmatic lithology and low to medium grade metamorphic rocks. The heavy mineral assemblage in the southern zone, consists of minerals like kyanite/sillimanite, rutile, zircon, garnet and staurolite which indicates metamorphic sources. However, the absence of high-grade metamorphic rocks in the catchment area of river Sharavati precludes the derivation of garnet and staurolite from the hinterland. Therefore, the presence of such minerals in southern zone may have been brought by strong northerly alongshore drift from further south (Kerala coast) where the high-grade metamorphic rocks are dominant. Similar results have been obtained in the studies on Mulki beach (Shalini et al., 2020). The iron oxides viz., hematite, V-hematite, magnetite, Ti-magnetite, V-magnetite, Ti–V-magnetite (Table 1) present in all the three zones of the study area reflect their origin from the iron ore bodies in the hinterland (Fig. 2).

Although the studies on modal composition of heavy minerals in the beach sands are useful for understanding the provenance, the recent development in provenance analysis based on mineral chemistry has provided significant information about their origin and genesis.

6 Conclusion

- The heavy mineral assemblage studies of beach sediments from Uttara Kannada coast corroborates with the lithology of catchment area indicating their derivation from both igneous and metamorphic suites.
- The euhedral zircon population depicts its derivation from the proximal granitoids in the hinterland whereas the sub-rounded to rounded zircons may have metasedimentary origin and/or undergone recycling of offshore sediments.
- Based on single-grain chemistry of heavy minerals, the spinel composition suggests its volcanic origin, particularly island-arc peridotites, corroborating with the ultramafic suite present in the catchment area of river Kali (northern zone) and Gangavali (central zone).
- The geochemistry of rutiles indicates metamorphic rocks as their major source.
- The tourmaline chemistry from the northern zone, confirms its derivation from granitoids in Devbhag beach and metamorphic rocks in Rabindranath Tagore beach. The southern zone tourmalines, however, depicts the dual origin nature corroborating the presence of both granites and migmatites in the catchment area.
- The ilmenite geochemistry indicates their derivation from gneissic rocks, minor being derived from the basic lithotype.
- The presence of iron oxides (hematite, V-hematite, magnetite, Ti-magnetite, V-magnetite, Ti–V-magnetite) in all three zones of the Uttara Kannada coast corroborates their origin from the iron ore bodies in the hinterland.

Despite of the facts that the provenance studies is based on the Uttara Kannada coast, India; the results indicating their mixed mode origin/alongshore drift enables to trace the sediment transport path ways. Hence, the principle has global application for exploration of coastal placer mineral deposits and/or tracing the sediment sources for coastal zone management.

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Author contributions PM and HVS conceived the presented idea. We developed the theory and performed the computations with the help of HS and PAR. HS and PAR also contributed towards field investigations and sample processing. MMK contributed in EPMA analysis and also helped in revising the manuscript. All authors contributed to the design and implementation of the research to the analysis of the results and to the writing of the manuscript.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Hereby, I, Mr. Manjunath Paltekar consciously assure that for the manuscript 'Geochemistry of heavy minerals from Uttara Kannada beach sediments, West Coast of India: An insight into provenance studies' the following is fulfilled: (1) This material is the authors' own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors' own research and analysis in a truthful and complete manner. (4) The paper properly credits the meaningful contributions of co-authors and co-researchers. (5) The results are appropriately placed in the context of prior and existing research. (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such using quotation marks and giving proper reference. (7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content. The violation of the Ethical Statement rules may result in severe consequences. I agree with the above statements and declare that this submission follows the policies Journal of Sedimentary Environments as outlined in the Guide for Authors and in the Ethical Statement.

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