

REE geochemistry of core sediments of Cauvery delta, India for provenance studies

Malik Zubair Ahmad¹ · Pramod Singh²

Received: 17 June 2019 / Revised: 15 September 2019 / Accepted: 17 October 2019 / Published online: 26 October 2019
© Science Press and Institute of Geochemistry, CAS and Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract The rare earth element (REE) geochemical composition of sediments from two cores were used to investigate the provenances of the Late Pleistocene to Holocene sediments of Cauvery delta, South India. The chondrite-normalized REE patterns and bi-variant plots of Th/Co vs. La/Sc and La/Th vs. Th/Yb indicated felsic source of sediments. Chondrite-normalized plots of REE in both cores are almost parallel and exhibit similar fractionation ratio $(Ce/Yb)_N$ of ~ 8.2 . Furthermore, persistence in REEs patterns implies either uniform source rocks and/or efficient homogenization of sediments during transportation and deposition. Chondrite-normalized patterns of the samples show enrichment of light rare earth elements and flat pattern of heavy rare earth elements; such patterns imply dominance of felsic composition rocks in the provenance. Further, these samples show quite resemblance with Charnockites and Gneisses of Palani and Kodaikanal hill areas. Chondrite-normalized REE patterns of the Pleistocene sediments of Uttrangudi core show similar abundance, fractionation, and Eu anomaly values as of selected samples from Tertiary rocks near southwest part of the delta. We attribute the increased input from this region to the upliftment because of tectonic activity and lowering of sea level during the Pleistocene.

Keywords Delta sediments · REEs · Provenance · Rainfall · Relief

1 Introduction

The chemical and mineralogical composition of clastic sedimentary rocks is the manifestation of composite interactions of several variables, including source rock composition, weathering, erosion, transportation, and sedimentation processes (Nesbitt and Young 1996; Singh and Rajamani 2001b; Tripathi and Rajamani 2007; Mir et al. 2015, 2016; Abedini and Calagari 2015). From the erosion of the source region until the final deposition, the sediments preserve the chemical signature of their provenance rocks (Dou et al. 2016). The Rare earth elements (REEs) in sediments are thought to be carried without showing any loss (Taylor and McLennan 1985). REEs are comparatively insoluble and found in low concentrations in sea and river waters. REEs are not easily fractionated during sedimentation and their patterns may provide a key to discovering average provenance compositions (Singh 2009; Mir, 2015; Garzanti and Resentini 2016). In addition, with similar behavior, the REEs are expected to retain their pattern and the ratios similar to their source rocks Fralick and Kronberg (1997). Factors that control the sediment load in rivers include relief, channel slope, basin size, seasonality of rains and tectonic activities (Chakrapani 2005). Relief plays an important role making geographical differences in rainfall distribution with windward side of mountains receiving large amounts of rain while leeward sides receive very little (Chakrapani 2005). In the studied area, the entire catchment of the Cauvery River lies in the rain shadow zone of south-west monsoon that is blocked by the Western Ghats located towards the west. The major contribution of rainfall

✉ Malik Zubair Ahmad
malikzubair.amu@gmail.com

Pramod Singh
pramods@yahoo.com

¹ Department of Geology, Satellite Campus Leh, University of Kashmir, Leh, Jammu & Kashmir 194104, India

² Department of Earth Sciences, School of Physical Chemical and Applied Sciences, Pondicherry University, Kalapet, Pondicherry 605014, India

in this region is from the NE monsoon (Venkatesh and Jose 2007). The sediments derived by rivers from its catchment region accumulate in coastal environments and form deltas (Wright, 1977; Ta et al. 2002; Chu et al. 2006). The main aim of the present study is to decipher the provenance of the Uttrangudi and the Porayar sediment cores of the Cauvery delta by using REEs and some immobile trace elements like Sc, Th, Co, etc.

2 Geological and climatic setting

The River Cauvery originates in the Brahmagiri range of the Western Ghats and flows 800 km to join the Bay of Bengal by draining an area of $\sim 87,900 \text{ km}^2$. Elevation varies from near sea level to around 1341 m above mean sea level (msl) in the upper reaches. The catchment area of the Cauvery River includes the northern greenstone granite belt of Dharwar Craton (DC) and the Southern Granulite Belt (SGB) separated by several N–S and E–W trending major shear zones (Swaminath et al. 1976; Meissner et al. 2001). In upper reaches, the river flows through the Dharwar Craton comprising of vast areas of Tonalite Trondjehmite gneisses (TTG-commonly known as Peninsular Gneisses) (Fig. 1). Based on the nature and abundance of greenstone belts, degree of regional metamorphism and melting, and age of their gneissic basement rocks, the Dharwar Craton has been subdivided into the western (WDC) and eastern blocks (EDC) (Chadwick et al. 1981, 2000). TTG type Peninsular gneisses of WDC are $\sim 3.4 \text{ Ga}$ old (Meen et al. 1992; Peucat et al. 1993) with major shear zones include Moyar, Bhavani, Palghat, Cauvery and Attur (Raith et al. 1999; Chadwick et al. 2000; Meisner et al. 2001). The SGB forming part of Cauvery catchment is delineated by the crustal-scale shear zones that have subdivided it into two major blocks; the Northern Granulite Block (NGB) and the Southern Granulite Block (SGB). The northern part of SGB consists of Meso-Neo Archean charnockite massifs of intermediate composition forming Nilgiri hills (NGH), Biligirirangan hills (BRG) and the Shevroy hill massif (Rajesh 2012), whereas the SGB consists of Palani-Kodaikanal massif of Madurai Block (MB). Cauvery River traverses its path through the above lithologies types and forms the delta east of Tiruchirappalli with exposed older rocks mainly of sedimentary origin bordering the present-day Cauvery delta. Towards north, it is bordered by Cretaceous sediments consisting of conglomerate sandstone, fossiliferous limestone, shale and the Tertiary upland formations of the Mio-Pliocene age mainly consisting of argillaceous, ferruginous sandstone and clay stones (Meijerink 1971). Presently, the Cauvery basin receives variable rainfall during both southwestern (Indian summer

monsoon) and northeastern (winter) monsoons. Northeast monsoon provides a greater portion of the annual precipitation. Generally, the basin experiences sub-humid to semi-arid climate. The western side of the catchment mainly experiences southwest monsoon (June to September) and northeast monsoon (October to December) falls on the eastern side. The drainage basin receives an average annual rainfall of 110 cm Sharma and Rajamani (2000). Most of the annual rainfall along the western border is during SW monsoon and accounts for 73% of annual water discharge and 85% of annual sediment transport (Pattanaik et al. 2013).

3 Methodology

Two sediment cores were recovered by diamond/Tungsten core drilling bit, involving a double-barrel core tube, from Uttrangudi and Porayar locations of Cauvery delta (Fig. 1). Uttrangudi (UG) core lies around 25 km inland from the Bay of Bengal coast near Tiruvarur area (N $10^{\circ}39' 17.7''$, E $79^{\circ}39' 42.2''$). At Porayar (PR), core sediment was collected around 2 km inland from the Bay of Bengal, located North Karaikal region (N $11^{\circ} 01' 17.8''$, E $79^{\circ} 50' 42.6''$) with local elevation of the site around 2 m above mean sea level. For grain size analysis, samples were taken after two centimeters and analyzed by laser particle size analyzer (Cillas 1190) pre-treated with excess 10% H_2O_2 in a water bath at 60°C for 1 h to remove any organic matter. Based on physical observations and textural analysis, 60 samples were selected from both cores at different intervals for major, trace and REE analysis. The bulk mineral analysis was carried using X-Ray Diffractometer (XRD) and identification of bulk minerals was done by standard procedures (Brindley and Brown 1980; Nesse 2000). For REEs analysis, sample digestion was carried out by NaOH and Na_2O_2 fusion method in nickel crucibles. Furthermore, REE separation and pre-concentration were done using HNO_3 and HCl cation exchange resin (Bio-Rad AG50-X8) column (for details see Singh and Rajamani 2001a, b). All the elements were analyzed using a JY ICP-AES (ULTIMA 2) using international and laboratory standards and subsequently analyzed by ICP-AES. For major and trace element determination, standard B-solution procedure of Shapiro and Brannock (1962) was followed. Trace elements like Sc, Co, U, Th, and Rb were analyzed by (Thermo scientific, Xseries-2), ICP-MS. Both precision and accuracy for major and trace elements are better than 2% and for REE, precision and accuracy are better than 5%. For low REE samples ($< 5 \times \text{chondrite}$) the precision was 5%–10% for Ce and Nd. The precision on repeated measurement for Th, Sc, Co, U Ta and, Nb is $< 3\%$ and the accuracy is better than 10%. Radiocarbon dating and optically stimulated

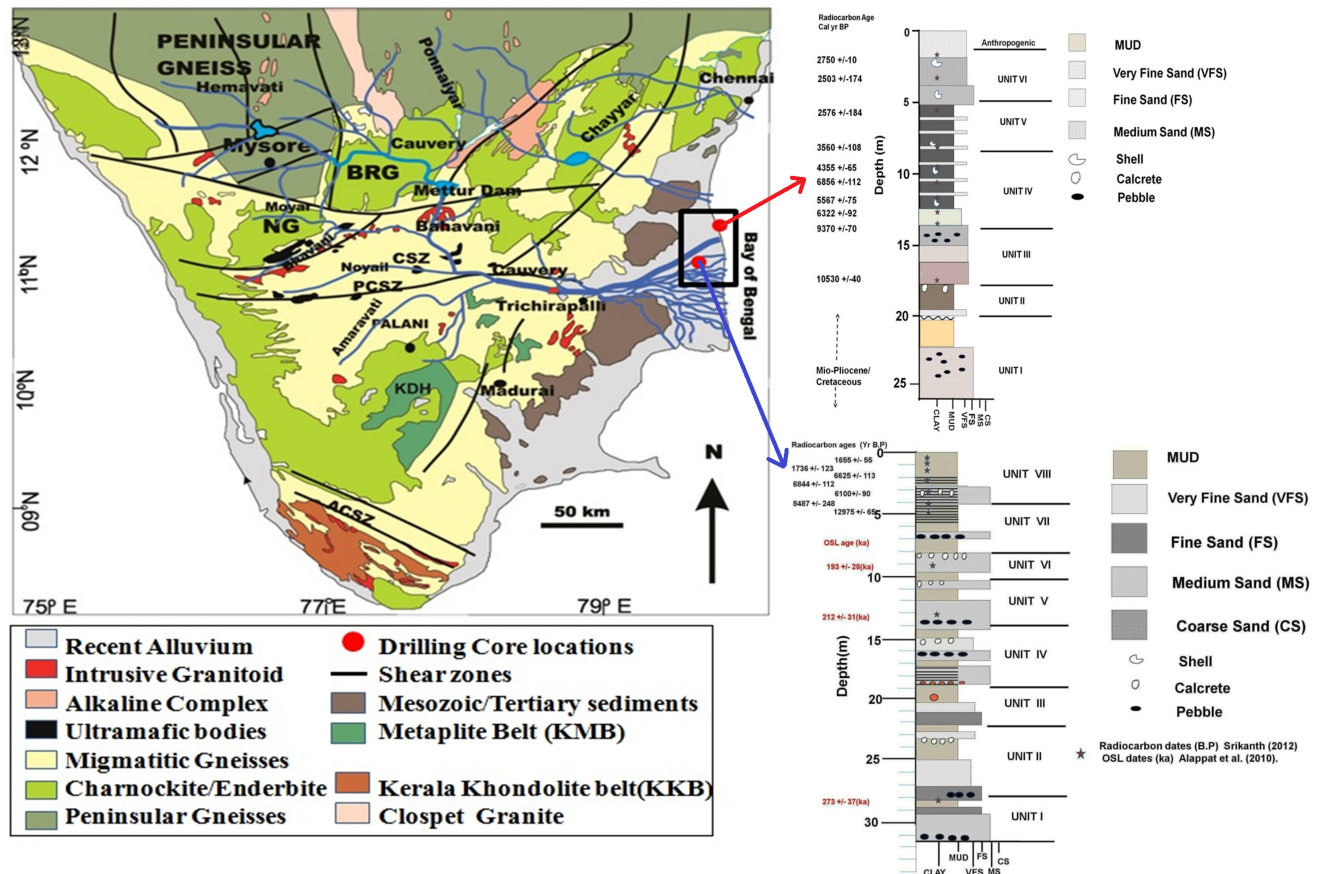


Fig. 1 Geological map of Cauvery Basin modified after (Santosh et al. 2009). Figure also shows the borehole lithology of two drilled cores

luminescence (OSL) dating was carried on same cores by (Alappat et al. 2010; Srikant 2012; Singh et al. 2015)

4 Results

The Utrangudi core sediments are of the middle to late Pleistocene and the Holocene age, whereas the Porayar core sediments are mostly of Holocene age, resting unconformably over older Tertiary/Cretaceous sedimentary rocks. Sediments of both the cores are composed of clayey silt, silt, sandy silt to silty sand, and gravely to pebbly sands. Colors in the sediments range from light brown, dark brown, grayish, greenish grey, grayish brown, grayish black to red. The presence of lateritic pebbles in the Pleistocene units indicates increased sediment input probably from the local laterite capped Mio-Pliocene sandstone and mudstone during Pleistocene which is exposed to the west of the core location. In some places, dispersed mottling is present whereas, some bands are completely mottled. Quartz and feldspar constitute major primary minerals whereas; smectite, kaolinite, and illite constitute the clay minerals. Illite is present in the entire depth in Porayar

location, whereas it is restricted to the Holocene in Utrangudi sediments and is absent in the Pleistocene sediments.

The chemical results of REEs in sediments from Utrangudi and Porayar core are given in Tables 1 and 2 respectively with number associated with the sample denoting the depth in cm. The total REE (Σ REE) concentration in sediments from Utrangudi core ranges from 52 to 246 ppm with an average value of 157 ppm. The average Σ REE concentration of sediments in Porayar site is 136 ppm ranging from 46 to 215 ppm except one sample at 8.3 m having a value of 270 ppm. The variety and concentration of REEs are higher in the Utrangudi sediments. As expected, the concentration of most individual REEs shows good correlation with each other and with Σ REE in both cores. In Utrangudi sediments the correlation coefficient (r) is 0.81 between La and Ce and 0.99 in the case of Sm and Gd. Similarly, it is 0.93 between Ce and Eu, and 0.99 between Gd and Yb in Porayar sediments. The range of ratios such as $(Ce/Yb)_N$, $(Ce/Sm)_N$ and $(Gd/Yb)_N$ ratios of Utrangudi sediments is 7.4 to 10.9, 2.5 to 4.0 and 1.4 to 2.7 respectively, except for three samples at 22.45 m, 23.28 and 23.88 that have lower $(Ce/Yb)_N$ values of 3.5,

Table 1 Rare earth element (REE) in (ppm) abundances along with chondrite normalized ratios of samples from Uttrangudi borehole. $Eu^* = Eu_N / (Sm_N \times Gd_N)^{1/2}$ (McLennan 1989)

	Depth	La	Ce	Nd	Sm	Eu	Gd	Dy	Yb	Lu	TREE	La/ Yb	Ce/ Yb	Eu*	La/ Sm	GD/ Yb	Ce/ Sm	Silt (%)	Sand (%)	MUD (%)
UG 83	83	54.7	115.9	44.9	9.3	2.1	7.8	6.3	3.4	0.5	244.9	10.9	8.9	0.7	3.7	1.8	3.0	50.8	47.1	52.9
UG 113	113	54.8	115.3	46.7	9.4	2.2	7.9	6.5	3.4	0.5	246.6	10.9	8.9	0.8	3.7	1.9	3.0	60.5	36.5	63.6
UG 185	185	50.8	104.3	43.8	8.8	1.9	7.3	5.9	3.2	0.5	226.6	10.6	8.4	0.7	3.6	1.8	2.9	61.9	35.2	64.8
UG 220	220	48.3	103.2	41.4	8.8	1.9	7.2	6.0	3.2	0.5	220.5	10.3	8.6	0.7	3.4	1.8	2.8	81.5		100.0
UG 240	240	46.3	102.1	41.3	8.9	2.0	7.3	6.2	3.3	0.5	217.8	9.5	8.1	0.7	3.2	1.8	2.8	45.3	53.1	46.9
UG 260	260	52.5	106.5	45.9	8.8	2.1	7.4	5.7	3.4	0.6	232.8	10.6	8.3	0.8	3.7	1.8	2.9	62.3	35.8	64.3
UG 280	290	28.0	57.9	22.2	4.4	1.1	3.6	2.9	1.9	0.2	122.2	9.9	7.9	0.8	3.9	1.5	3.1	37.0	61.7	38.3
UG 313	319	25.0	54.9	19.3	4.0	1.0	3.2	2.5	1.6	0.4	111.7	10.6	9.0	0.8	3.9	1.6	3.3	26.5	72.1	27.9
UG 380	380	21.1	42.3	16.3	3.4	0.8	2.8	2.3	1.5	0.2	90.7	9.5	7.4	0.8	3.9	1.5	3.0	20.6	78.6	21.4
UG 392	392	29.4	54.6	21.9	4.5	1.0	3.7	3.1	1.9	0.3	120.4	10.4	7.5	0.8	4.1	1.6	2.9	23.3	75.7	24.3
UG 419	419	45.0	77.1	35.7	7.0	1.8	6.6	5.2	2.7	0.4	181.5	11.5	7.6	0.8	4.0	2.0	2.6	50.9	46.8	53.2
UG 427	427	34.9	82.8	29.1	5.9	1.4	4.9	3.7	2.3	0.3	165.5	10.2	9.4	0.8	3.7	1.7	3.4	50.9	46.8	53.2
UG 457	457	38.8	90.4	32.3	6.5	1.5	4.9	3.9	2.2	0.4	180.9	12.1	10.9	0.8	3.7	1.8	3.3	66.1	31.4	68.6
UG 477	477	45.0	89.3	39.0	7.7	1.8	6.2	4.8	2.8	0.6	197.1	11.0	8.5	0.8	3.6	1.8	2.8	57.3	40.5	59.6
UG 526	526	39.8	85.9	33.2	6.7	1.6	5.1	4.1	2.4	0.5	179.3	11.4	9.5	0.8	3.7	1.7	3.1	58.6	29.1	70.9
UG 546	546	33.8	73.0	27.6	5.6	1.4	4.4	3.6	2.1	0.3	151.8	10.7	9.0	0.8	3.7	1.7	3.1	67.9	28.3	71.7
UG 566	566	41.5	89.7	34.5	7.4	1.8	6.2	5.0	2.8	0.6	189.4	10.0	8.3	0.8	3.5	1.8	2.9	56.8	40.3	59.7
UG 650	650	37.8	69.3	29.8	5.9	1.4	5.0	3.6	2.1	0.4	155.3	12.2	8.6	0.8	4.0	1.9	2.8	60.5	36.5	63.6
UG 815	815	36.8	100.1	32.1	6.9	1.7	6.2	4.9	3.1	0.6	192.4	8.0	8.5	0.8	3.3	1.6	3.5	71.6	26.0	74.0
UG 825	835	43.3	72.3	34.7	6.6	1.7	5.8	4.3	2.4	0.4	171.4	12.4	8.0	0.8	4.1	2.0	2.6	67.9	29.5	70.5
UG 855	855	23.2	44.4	18.0	3.6	1.1	3.2	2.5	1.4	0.2	97.6	11.3	8.3	1.0	4.1	1.9	3.0	42.8	55.6	44.5
UG 1010	1010	44.8	113.0	36.7	7.6	1.8	6.4	5.0	3.0	0.6	218.8	10.2	9.9	0.8	3.7	1.7	3.6	85.6	10.5	89.5
UG1200	1200	46.4	81.6	40.0	7.2	1.8	6.0	4.5	2.8	0.5	190.9	11.3	7.7	0.8	4.0	1.8	2.7	65.6	31.7	68.3
UG 1430	1430	36.7	77.1	29.4	5.9	1.4	5.2	3.8	2.4	0.5	162.3	10.6	8.6	0.8	3.9	1.8	3.2	78.9	19.0	81.0
UG 1510	1510	23.9	61.6	18.4	3.7	0.9	3.1	2.4	1.8	0.4	116.2	9.2	9.2	0.8	4.1	1.4	4.0	46.8	51.4	48.6
UG 1703	1703	24.4	57.4	18.5	3.8	0.9	3.0	2.2	1.6	0.4	112.1	10.4	9.5	0.8	4.0	1.5	3.7	60.5	36.5	63.6
UG1912	1912	43.7	101.0	36.3	7.8	1.8	6.6	5.4	3.3	0.7	206.6	9.1	8.1	0.8	3.5	1.6	3.1	88.8	8.7	91.3
UG 2098	2098	15.9	50.7	13.2	3.2	0.7	2.8	2.1	1.4	0.3	90.4	7.7	9.6	0.7	3.1	1.6	3.8	40.2	58.7	41.3
UG 2138	2138	28.4	75.1	22.9	4.9	1.1	4.3	3.5	2.2	0.4	142.8	8.8	9.0	0.7	3.6	1.6	3.7	49.5	49.0	51.0
UG 2245	2245	18.3	31.5	14.3	3.1	0.7	3.1	2.8	2.4	0.6	76.9	5.2	3.5	0.7	3.7	1.0	2.5	58.4	40.0	60.0
UG 2328	2328	14.0	24.6	8.0	1.5	0.4	1.4	1.4	1.1	0.2	52.6	8.9	6.0	0.8	5.8	1.1	3.9	48.7	49.8	50.2
UG 2388	2490	21.9	17.8	10.1	1.9	0.4	1.6	1.3	1.3	0.3	56.4	7.9	3.7	0.7	4.8	1.0	2.3	56.9	41.4	58.6
UG 2490	2490	35.7	34.8	21.7	3.3	0.7	2.3	1.8	1.2	0.2	101.8	20.6	7.8	0.8	6.7	1.6	2.5	65.8	31.9	68.1
UG 2760	2760	70.9	85.8	48.6	8.4	2.2	7.4	4.7	2.2	0.4	230.5	21.8	10.2	0.8	5.3	2.7	2.5	60.3	37.7	62.3

6.01 and 3.7 respectively and $(Gd/Yb)_N$ value of 1. In Porayar sediments, $(Ce/Yb)_N$, $(Ce/Sm)_N$ and $(Gd/Yb)_N$ ratio ranges from 5.3 to 8.3, 2.2 to 3.3 and 1.4 to 2.1 respectively. The Uttrangudi sediments exhibit slight negative Eu anomaly values ranging between 0.79 and 0.97, whereas Porayar sediments exhibit negative to slightly positive Eu anomalies ranging between 0.7 and 1.6.

REE concentrations in both the cores show a good positive correlation among them and with silt (%) and a negative correlation with sand (%). The finer sediments are having a higher concentration of REE. A good positive correlation of various REEs with silt ($r = 0.58$) and clay

($r = 0.6$) and negative correlation with sand ($r = 0.58$) percentage suggests that in majority of the studied sediments, REE holding mineral phases are concentrated in silt and clay fraction. The REEs in Uttrangudi sediments show good positive correlation with Th ($r = 0.73$) and Y ($r = 0.78$), moderate positive correlation with Al ($r = 0.63$), Fe ($r = 0.64$), Mg ($r = 0.65$), Mn ($r = 0.63$), Ni ($r = 0.64$), Cr ($r = 0.65$), Sc ($r = 0.58$), Co ($r = 0.57$), and poor correlation with Ti ($r = 0.4$) (Table 3). In the Porayar sediments, the REEs show positive correlations with Al ($r = 0.83$), Fe ($r = 0.84$), Mg ($r = 0.90$), Ti ($r = 0.81$), Th ($r = 0.81$), Y ($r = 0.87$), Ni ($r = 0.73$), Cr ($r = 0.85$), Sc

Table 2 Rare earth element (REE) abundances in (ppm) along with chondrite normalized ratios of samples from Porayar borehole. $Eu^* = Eu_N / (Sm_N \times Gd_N)^{1/2}$ (McLennan 1989)

Depth	La	Ce	Nd	Sm	Eu	Gd	Dy	Yb	Lu	TREE	La/Yb	Ce/Yb	Eu*	La/Sm	GD/Yb	Ce/Sm	Clay (%)	Silt (%)	Sand (%)	Mud
PR 283	283	16.5	28.7	12.1	2.7	1.0	2.2	1.8	1.1	0.2	66.2	10.3	6.9	1.2	3.8	2.6	3.3	28.8	68.0	32.0
PR 329	329	31.3	47.4	23.4	4.0	1.3	4.0	3.3	2.1	1.0	117.7	10.0	5.8	1.0	4.9	2.9	0.8	23.0	76.2	23.8
PR 426	426	12.5	19.6	7.9	1.8	0.8	1.4	1.2	0.7	0.1	46.0	13.0	7.9	1.6	4.5	2.7	0.7	10.3	89.0	11.0
PR 548	548	52.3	96.5	40.1	7.0	2.1	6.7	5.8	3.1	0.4	214.0	11.4	8.1	0.9	4.6	1.7	1.2	46.8	52.0	48.0
PR 645	645	44.4	90.4	35.4	7.1	1.8	6.0	5.0	3.2	0.5	193.8	9.5	7.5	0.8	3.9	3.1	1.1	41.1	57.9	42.1
PR 775	775	47.2	89.6	39.2	7.2	1.8	7.6	5.5	3.1	0.6	201.9	10.3	7.6	0.7	4.1	2.0	5.3	63.4	31.3	68.7
PR 831	831	60.2	124.6	51.9	9.6	2.4	9.2	7.3	4.3	0.7	270.2	9.4	7.5	0.8	3.9	1.7	14.2	83.3	2.4	97.6
PR 842	842	37.1	73.8	31.4	6.5	1.4	5.9	4.4	2.6	0.4	163.7	9.6	7.4	0.7	3.6	1.8	2.2	58.0	39.8	60.2
PR 945	945	42.6	83.6	36.6	7.3	1.9	6.1	4.9	2.7	0.6	186.2	10.8	8.2	0.9	3.6	1.8	11.4	67.0	21.6	78.4
PR 1029	1029	18.3	34.1	14.2	3.1	0.9	2.5	2.0	1.1	0.2	76.5	11.4	8.2	1.0	3.6	1.9	7.2	45.6	47.2	52.8
PR 1170	1170	28.3	55.4	22.8	5.0	1.4	4.0	3.0	2.0	0.5	122.3	9.8	7.4	1.0	3.6	1.7	10.4	56.1	33.5	66.5
PR 1226	1226	28.2	50.1	22.2	4.9	1.4	4.0	3.1	2.2	0.5	116.6	8.9	6.1	1.0	3.6	1.5	7.0	46.5	46.5	53.5
PR 1279	1279	21.0	36.2	16.2	3.8	1.2	3.0	2.2	1.6	0.4	85.5	9.1	6.1	1.1	3.5	1.5	6.3	44.9	48.8	51.2
PR 1351	1351	21.2	40.4	16.5	3.5	1.1	2.7	2.4	1.5	0.3	89.7	9.5	7.0	1.0	3.7	1.4	3.4	49.1	47.5	52.5
PR 1453	1453	30.0	49.6	23.7	5.1	1.6	4.5	3.4	2.4	0.5	120.8	8.4	5.3	1.0	3.7	1.5				
PR 1483	1483	30.4	53.8	23.7	5.3	1.6	4.5	3.5	2.4	0.6	125.9	8.6	5.9	1.0	3.6	1.5	2.6	41.4	56.0	44.0
PR 1573	1573	28.8	54.1	24.2	4.9	1.2	3.9	3.1	2.0	0.4	122.7	9.9	7.2	0.9	3.7	1.6	2.8	38.8	58.4	41.6
PR 1643	1643	36.3	61.4	25.8	5.0	1.5	4.1	3.0	2.3	0.2	139.5	10.5	6.9	1.0	4.6	1.4	1.5	35.2	63.4	36.6
PR 1718	1718	21.2	37.7	16.1	3.7	1.1	3.0	2.2	1.7	0.4	87.1	8.7	6.0	1.0	3.6	1.5	4.9	47.8	47.3	52.7
PR 1785	1785	30.3	47.0	25.2	5.2	1.3	4.6	3.6	1.8	0.3	119.3	11.6	7.0	0.8	3.6	2.1	6.6	77.8	15.5	84.5
PR 1833	1833	37.0	83.9	30.2	6.5	1.7	5.6	4.4	2.8	0.6	172.7	9.0	7.9	0.9	3.6	1.6	7.0	92.9	0.1	99.9
PR 1863	1863	49.4	95.8	41.9	8.6	2.4	7.9	5.8	3.2	0.6	215.5	10.4	7.8	0.9	3.6	2.0				
PR 1923	1923	35.9	68.8	28.7	6.0	1.6	4.9	4.0	2.2	0.4	152.4	11.3	8.3	0.9	3.8	1.8	5.8	74.4	19.8	80.2
PR 1953	1953	29.3	56.2	24.2	4.8	1.3	4.1	3.3	1.9	0.4	125.4	10.3	7.6	0.9	3.8	1.7	4.1	58.5	37.4	62.6
PR 2170	2170	27.6	58.5	23.2	4.8	1.2	3.8	3.2	2.0	0.3	124.6	9.2	7.5	0.8	3.6	1.5	0.8	28.6	70.7	29.4
PR 2348	2348	40.4	77.6	33.8	6.8	1.7	5.5	4.5	2.7	0.5	173.6	10.0	7.4	0.8	3.7	1.6	1.9	54.8	43.3	56.7

	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	MgO	MnO	Ca*O	Na* ₂ O	K ₂ O	P ₂ O ₅	Ba	Sr	Cr	Ni	Sc	Co	Th	U	Y	Rb	La	Ce	Nd	Sm	Eu	Gd
SiO ₂	1.00																									
Al ₂ O ₃	− 0.98	1.00																								
TiO ₂	− 0.73	0.68	1.00																							
Fe ₂ O ₃	− 0.97	0.97	0.76	1.00																						
MgO	− 0.93	0.88	0.63	0.88	1.00																					
MnO	− 0.58	0.54	0.48	0.56	0.59	1.00																				
Ca*O	− 0.53	0.39	0.37	0.39	0.62	0.38	1.00																			
Na* ₂ O	− 0.82	0.73	0.56	0.70	0.78	0.44	0.77	1.00																		
K ₂ O	− 0.86	0.78	0.62	0.75	0.84	0.50	0.71	0.88	1.00																	
P ₂ O ₅	− 0.80	0.76	0.70	0.78	0.67	0.36	0.38	0.80	0.72	1.00																
Ba	− 0.59	0.52	0.44	0.50	0.66	0.78	0.61	0.61	0.69	0.35	1.00															
Sr	− 0.56	0.45	0.31	0.43	0.68	0.46	0.90	0.67	0.71	0.29	0.71	1.00														
Cr	− 0.85	0.88	0.57	0.84	0.72	0.47	0.25	0.67	0.69	0.67	0.50	0.27	1.00													
Ni	− 0.85	0.87	0.52	0.88	0.76	0.51	0.27	0.54	0.62	0.56	0.44	0.36	0.83	1.00												
Sc	− 0.75	0.75	0.44	0.76	0.79	0.45	0.26	0.50	0.61	0.59	0.38	0.34	0.66	0.72	1.00											
Co	− 0.52	0.50	0.25	0.52	0.59	0.63	0.24	0.40	0.46	0.40	0.54	0.29	0.41	0.50	0.77	1.00										
Th	− 0.75	0.77	0.61	0.77	0.70	0.41	0.17	0.39	0.64	0.47	0.47	0.26	0.74	0.76	0.65	0.42	1.00									
U	− 0.71	0.69	0.42	0.73	0.77	0.46	0.35	0.40	0.65	0.42	0.46	0.47	0.54	0.79	0.73	0.55	0.76	1.00								
Y	− 0.76	0.76	0.50	0.76	0.65	0.56	0.28	0.57	0.67	0.57	0.60	0.39	0.72	0.79	0.62	0.56	0.72	0.71	1.00							
Rb	− 0.73	0.67	0.45	0.66	0.81	0.48	0.52	0.66	0.82	0.64	0.54	0.55	0.53	0.54	0.84	0.74	0.57	0.73	0.58	1.00						
La	− 0.55	0.53	0.32	0.54	0.57	0.45	0.36	0.47	0.50	0.24	0.57	0.42	0.58	0.51	0.56	0.46	0.71	0.63	0.64	0.53	1.00					
Ce	− 0.65	0.63	0.43	0.63	0.63	0.68	0.38	0.49	0.61	0.33	0.70	0.49	0.62	0.65	0.55	0.59	0.71	0.66	0.79	0.56	0.81					

	Dy	Yb	Lu	Σ_{REE}
Dy	1.00			
Yb	0.96	1.00		
Lu	0.65	0.78	1.00	
Σ_{REE}	0.96	0.90	0.62	1.00

Table 4 Correlation matrix for major, trace element concentration and Σ REE of samples from Porayar borehole

	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	MgO	MnO	Ca*O	Na* ₂ O	K ₂ O	P ₂ O ₅	Mz	Ba	Sr	Cr		
SiO ₂	1.00															
Al ₂ O ₃	– 0.98	1.00														
TiO ₂	– 0.77	0.73	1.00													
Fe ₂ O ₃	– 0.92	0.89	0.84	1.00												
MgO	– 0.93	0.89	0.79	0.97	1.00											
MnO	– 0.66	0.61	0.62	0.73	0.74	1.00										
Ca*O	0.20	– 0.27	– 0.26	– 0.49	– 0.40	– 0.34	1.00									
Na* ₂ O	0.26	– 0.31	– 0.47	– 0.57	– 0.52	– 0.41	0.81	1.00								
K ₂ O	– 0.74	0.73	0.41	0.56	0.57	0.50	– 0.10	0.08	1.00							
P ₂ O ₅	– 0.31	0.30	– 0.20	0.12	0.29	0.18	0.19	0.27	0.24	1.00						
Mz	0.80	– 0.76	– 0.69	– 0.74	– 0.76	– 0.65	0.04	0.23	– 0.67	– 0.15	1.00					
Ba	0.33	– 0.32	– 0.45	– 0.58	– 0.50	– 0.25	0.61	0.64	– 0.05	0.21	0.12	1.00				
Sr	0.31	– 0.29	– 0.38	– 0.60	– 0.52	– 0.40	0.80	0.71	– 0.11	0.19	0.14	0.88	1.00			
Cr	– 0.89	0.87	0.85	0.95	0.91	0.69	– 0.43	– 0.50	0.55	0.09	– 0.79	– 0.52	– 0.53	1.00		
Ni	– 0.80	0.79	0.58	0.80	0.86	0.63	– 0.28	– 0.44	0.40	0.43	– 0.67	– 0.29	– 0.30	0.76		
Sc	– 0.82	0.81	0.87	0.95	0.87	0.71	– 0.55	– 0.61	0.49	– 0.14	– 0.69	– 0.55	– 0.64	0.89		
Co	– 0.83	0.81	0.83	0.93	0.88	0.82	– 0.50	– 0.58	0.58	– 0.06	– 0.79	– 0.49	– 0.61	0.88		
Th	– 0.76	0.72	0.90	0.89	0.83	0.75	– 0.40	– 0.59	0.43	– 0.22	– 0.73	– 0.51	– 0.56	0.84		
Y	– 0.84	0.79	0.88	0.88	0.83	0.74	– 0.27	– 0.41	0.53	0.00	– 0.80	– 0.29	– 0.33	0.88		
Rb	– 0.84	0.85	0.66	0.91	0.89	0.75	– 0.57	– 0.55	0.58	0.12	– 0.64	– 0.51	– 0.63	0.79		
La	– 0.88	0.81	0.83	0.86	0.87	0.66	– 0.10	– 0.30	0.51	0.23	– 0.67	– 0.37	– 0.32	0.81		
Ce	– 0.90	0.84	0.83	0.91	0.91	0.64	– 0.20	– 0.37	0.49	0.26	– 0.67	– 0.47	– 0.41	0.86		
Nd	– 0.88	0.82	0.85	0.89	0.89	0.69	– 0.16	– 0.36	0.51	0.18	– 0.69	– 0.43	– 0.38	0.84		
Sm	– 0.87	0.81	0.87	0.91	0.89	0.67	– 0.22	– 0.42	0.49	0.13	– 0.72	– 0.46	– 0.41	0.86		
Eu	– 0.87	0.82	0.81	0.85	0.84	0.56	– 0.14	– 0.31	0.54	0.17	– 0.71	– 0.30	– 0.26	0.79		
Gd	– 0.88	0.83	0.84	0.90	0.89	0.71	– 0.22	– 0.39	0.53	0.16	– 0.70	– 0.41	– 0.40	0.85		
Dy	– 0.89	0.84	0.82	0.90	0.90	0.70	– 0.20	– 0.37	0.53	0.21	– 0.69	– 0.43	– 0.40	0.84		
Yb	– 0.83	0.77	0.83	0.84	0.83	0.60	– 0.13	– 0.33	0.44	0.18	– 0.63	– 0.41	– 0.33	0.79		
Lu	– 0.48	0.46	0.53	0.49	0.48	0.26	– 0.13	– 0.23	0.33	– 0.06	– 0.29	– 0.27	– 0.25	0.37		
ΣREE	– 0.89	0.83	0.84	0.90	0.90	0.66	– 0.17	– 0.35	0.51	0.23	– 0.68	– 0.44	– 0.38	0.85		
	Ni	Sc	Co	Th	Y	Rb	La	Ce	Nd	Sm	Eu	Gd	Dy	Yb	Lu	ΣREE
SiO ₂																
Al ₂ O ₃																
TiO ₂																
Fe ₂ O ₃																

Table 4 continued

	Ni	Sc	Co	Th	Y	Rb	La	Ce	Nd	Sm	Eu	Gd	Dy	Yb	Lu	Σ REE
MgO																
MnO																
Ca*O																
Na* ₂ O																
K ₂ O																
P ₂ O ₅																
Mz																
Ba																
Sr																
Cr																
Ni	1.00															
Sc	0.66	1.00														
Co	0.64	0.95	1.00													
Th	0.66	0.93	0.90	1.00												
Y	0.69	0.89	0.89	0.87	1.00											
Rb	0.74	0.88	0.88	0.83	0.73	1.00										
La	0.71	0.81	0.79	0.79	0.86	0.72	1.00									
Ce	0.75	0.83	0.80	0.79	0.85	0.76	0.98	1.00								
Nd	0.70	0.86	0.84	0.84	0.88	0.77	0.99	0.98	1.00							
Sm	0.69	0.88	0.87	0.84	0.91	0.77	0.96	0.97	0.98	1.00						
Eu	0.68	0.82	0.80	0.76	0.88	0.72	0.95	0.93	0.95	0.95	1.00					
Gd	0.70	0.87	0.86	0.84	0.90	0.80	0.97	0.97	0.99	0.98	0.95	1.00				
Dy	0.70	0.85	0.85	0.81	0.87	0.79	0.98	0.98	0.99	0.98	0.95	0.99	1.00			
Yb	0.65	0.80	0.78	0.79	0.86	0.70	0.96	0.96	0.96	0.96	0.94	0.96	0.96	1.00		
Lu	0.15	0.53	0.54	0.53	0.45	0.51	0.58	0.53	0.58	0.56	0.60	0.61	0.60	0.65	1.00	
Σ REE	0.73	0.84	0.82	0.81	0.87	0.76	0.99	1.00	1.00	0.98	0.95	0.98	0.99	0.97	0.57	1.00

($r = 0.84$), Co ($r = 0.82$) and moderate correlation with Mn ($r = 0.66$) (Table 4). Such positive correlations of REEs in both the core sediments indicate the role of mafic minerals and clay. In addition, the strong positive correlation of REEs with Ti, Th, and Y in Porayar sediments may suggest control of allanite, titanite, monazite, and zircon whereas poor correlation of REEs with Ti and good correlation with Th and Y in Uttrangudi sediments suggests the control of monazite and zircon.

5 Provenance

The chondrite-normalized REE patterns of both core sediments are almost similar which may indicate either uniform source rocks and/or efficient mixing of source lithologies during sediment transport and deposition (McLennan 1989). The enriched nature of the Light Rare Earth Elements (LREE) and flatter Heavy Rare Earth Elements (HREE) along with slight negative to positive Eu

anomalies, suggest that the sediments have been derived from rocks having felsic composition (Fig. 2). The immobile elements such as Th, Sc, Co, and REEs are relatively insoluble and have been found to be affected by geological processes, including weathering, transport, and sorting. Thus, these trace elements are powerful geochemical tracers for sediment provenance characterization (Tripathi and Rajamani 1999; Singh 2009; Yang et al. 2007; Botsou et al. 2015; Abedini et al. 2018). Th/Co versus La/Sc plot shows that the sediments for the studied samples had been derived from felsic provenance (Fig. 3). The La/Th versus Th/Yb plot has been used to differentiate between the felsic and mafic nature of source rocks Bhatia and Crook (1986). As shown in Fig. 4, the studied samples show the felsic character of source rocks. The core samples in the La–Th–Sc (Fig. 5) compositional diagram fall between the mixed-sedimentary and felsic field close to upper continental crust (UCC) and post-Archean Australian shale (PAAS), indicating that the sediments were probably derived from a source similar to a mixed sedimentary–

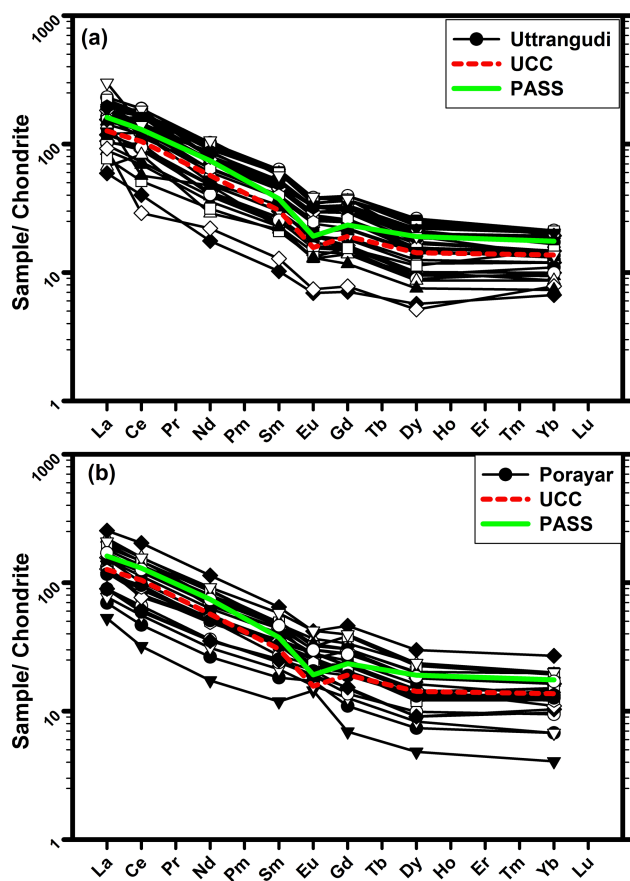


Fig. 2 Chondrite-normalized REE plots of sediments from **a** Uttrangudi (UG) and **b** Porayar (PR) cores. Also plotted for comparison are chondrite-normalized REE plots of UCC and PAAS

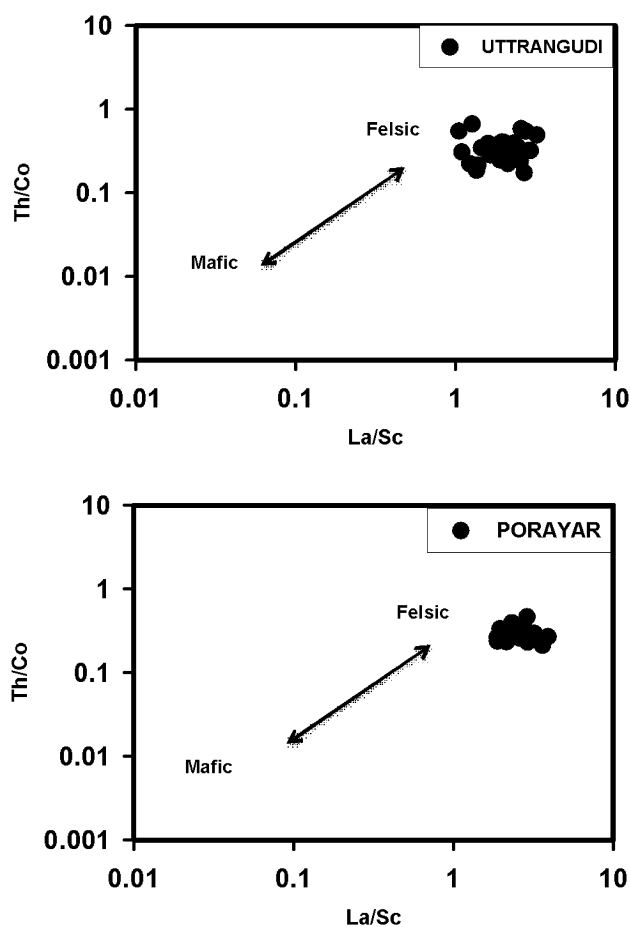


Fig. 3 Th/Co versus La/Sc for the samples. The logarithmic plot shows that the samples are sourced from felsic and intermediate provenance

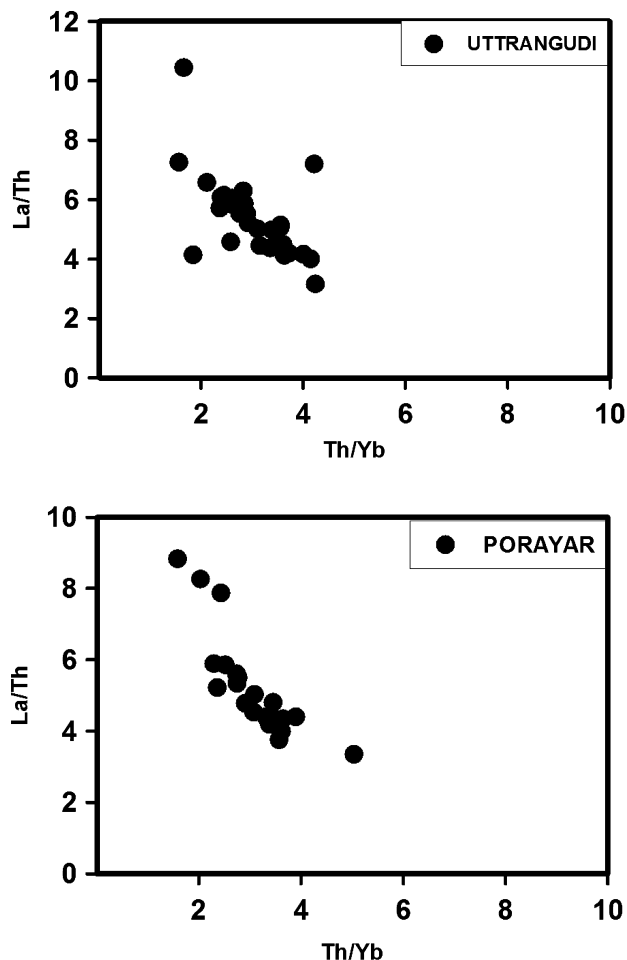


Fig. 4 La/Th versus Th/Yb plot showing felsic versus mafic character after (Taylor and McLennan 1985)

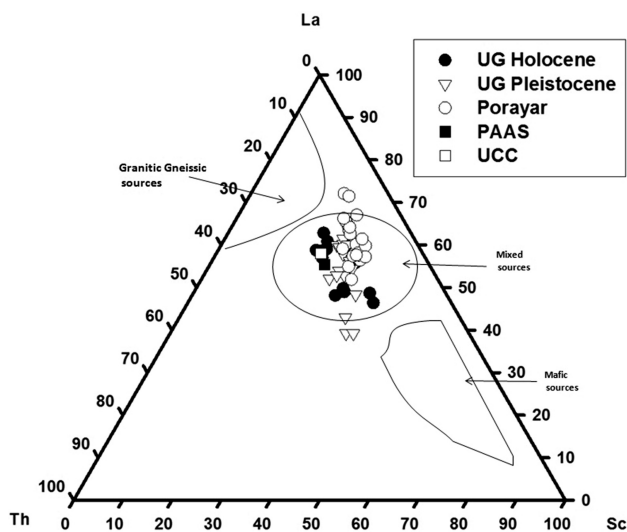


Fig. 5 The plot of core samples in La–Th–Sc compositional space that fall between the mixed-sedimentary field and felsic field close to UCC and PAAS

metasedimentary provenance Cullers (1994). This indicates that despite weathering and sediment transport, La, Th, and Sc have remained immobile during deposition of the sediments.

The chondrite-normalized REE patterns of the studied cores have been compared with chondrite-normalized patterns of various rock types like [(i) gneisses from the upper catchment of Mysore plateau (Bhaskar et al. 1991; Divakar Rao et al. 1999), (ii) enderbites from the Nilgiri Hills (Raith et al. 1999) and (iii) charnockites and migmatitic gneisses from shear zones and Kodaikanal Hills (Catlos et al. 2011; Plavsa et al. 2012)] to constrain the possible source rocks of the studied core sediments. The Cauvery River during its initial stage traverses over gneisses of Dharwar craton. By comparing the REEs plots of the sediments with gneissic rocks from the Dharwar Craton some noticeable differences are observed (Figs. 6a and 7a). The gneissic rocks of Dharwar craton show LREE fractionation similar to the sediments, whereas their HREE are more fractionated. In addition, they possess a moderate negative Eu anomaly (0.5–0.7). This suggests that the Gneisses of Dharwar Craton have not been the source of the sediments. The Cauvery River takes a bend after Hogenekal and starts flowing in a southerly direction entering plains after Mettur. In this part of its course, it is joined in the west by Bhavani River, a major tributary formed by the confluence of Moyar and Bhavani River flowing north and south of the Nilgiri hills. The Nilgiri hill in the SGB is comprised of intermediate charnockites that are of garnetiferous and non-garnetiferous nature (Raith et al. 1999; Rajesh 2012). The garnetiferous charnockite is depleted in LREE and exhibits HREE enrichment and has negligible negative Eu anomaly. The overall resultant chondrite-normalized REE pattern is less fractionated with $(Ce/Yb)_N$ values of ~ 5 . Compared to the sediments from both the cores; the garnetiferous charnockites are depleted in LREE, whereas the HREE exhibit a similar abundance and similar or less fractionation. The non-garnetiferous charnockites on the other hand, show a similar pattern. It is LREE enriched which is similar to the sediments. However, the HREE in these rocks show higher fractionation in comparison to the sediments. Thus, individually the REE patterns of both the charnockites, except their Eu anomaly do not match with the sediments (Figs. 6b and 7b). At the same time, their mix in almost equal proportion may result in REE pattern and abundance similar to the sediments, including the Eu anomaly. Moving further south, the River after Erode takes an easterly turn and continues flowing east along the Cauvery Shear Zone (CSZ) until it drains into the Bay of Bengal. The southern part of the SGB grouped as the Southern Granulite Block (SGB) lies to the south of Cauvery River in this part. The SGB includes Northern Madurai Block (NMB) made of massif

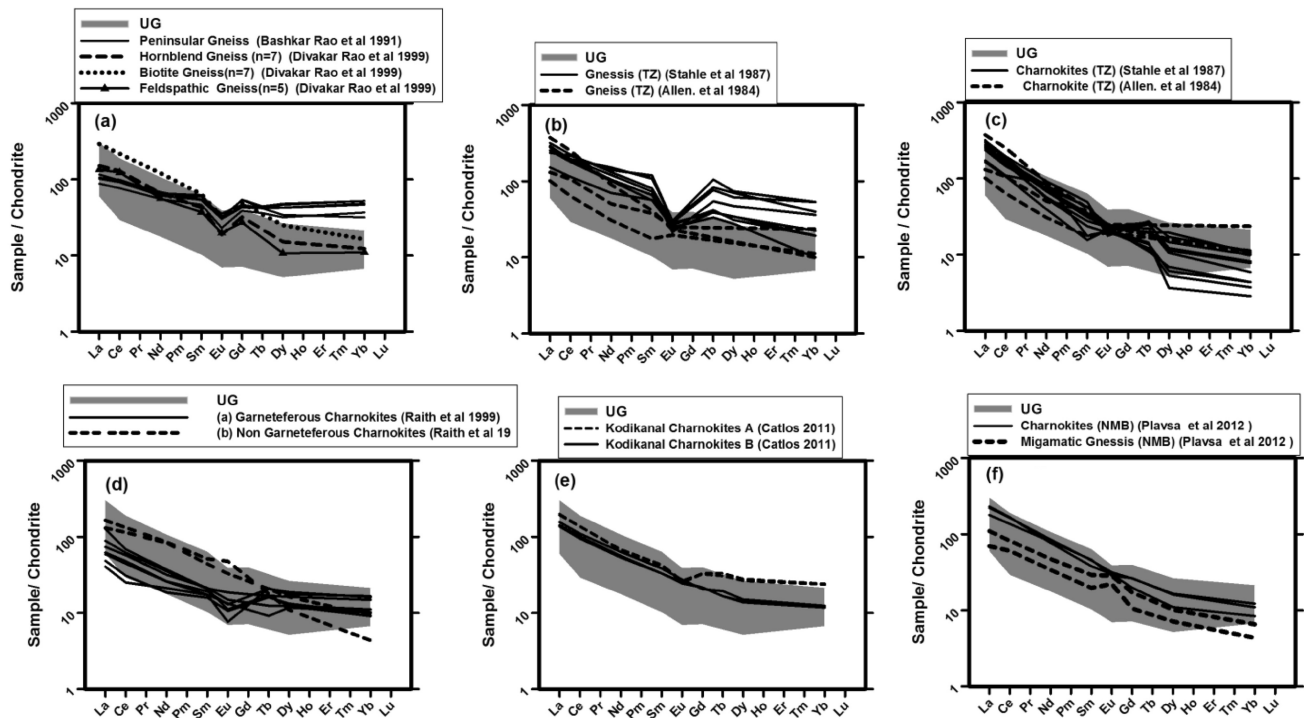


Fig. 6 The chondrite- normalized REE pattern value of studied sediments from Utrangudi core (shaded area) with **a** Gneisses Mysore plateau (Upper catchment) **b** enderbites from the Nilgiri Hills **c** and **d** Charnockites and Migmatitic gneisses from Kodaikanal Hills and Northern Madurai Block (NMB)

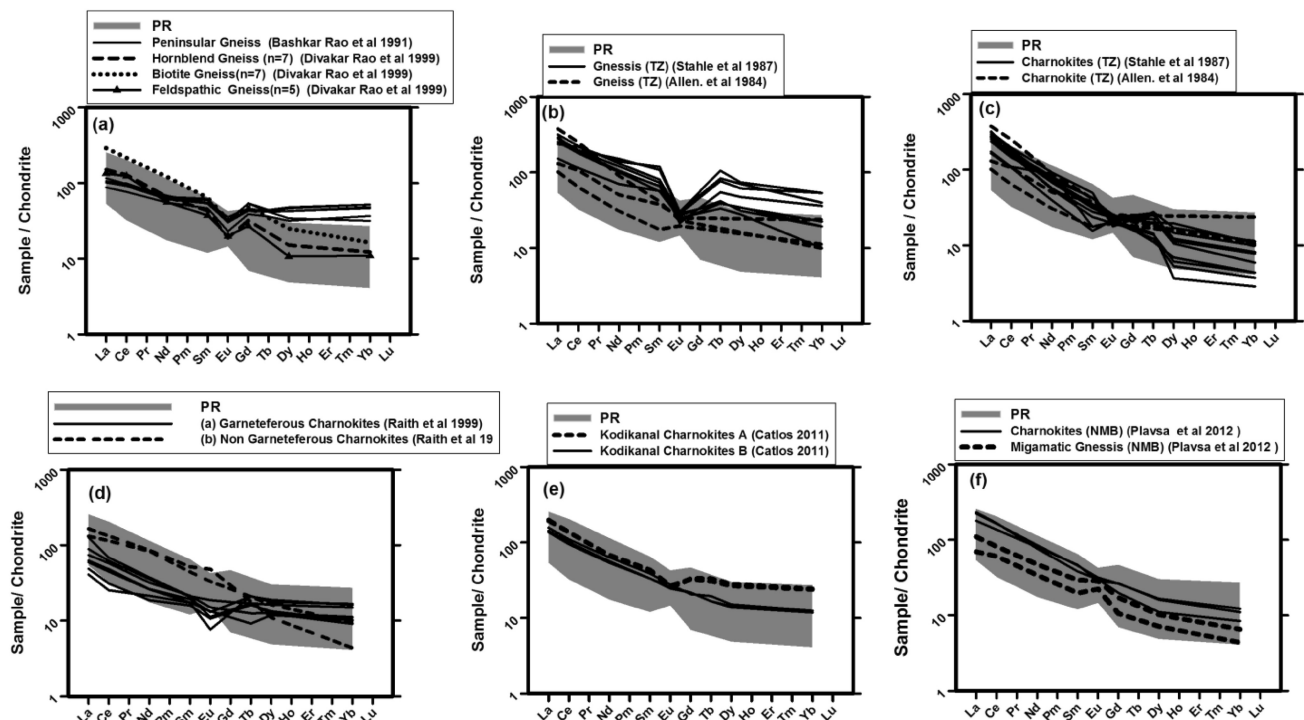


Fig. 7 The chondrite-normalized value of studied sediments from Porayar core (shaded area) with **a** Gneisses Mysore plateau (Upper catchment) **b** enderbites from the Nilgiri Hills **c** and **d** Charnockites and Migmatitic gneisses from Kodaikanal Hills and Northern Madurai Block (NMB)

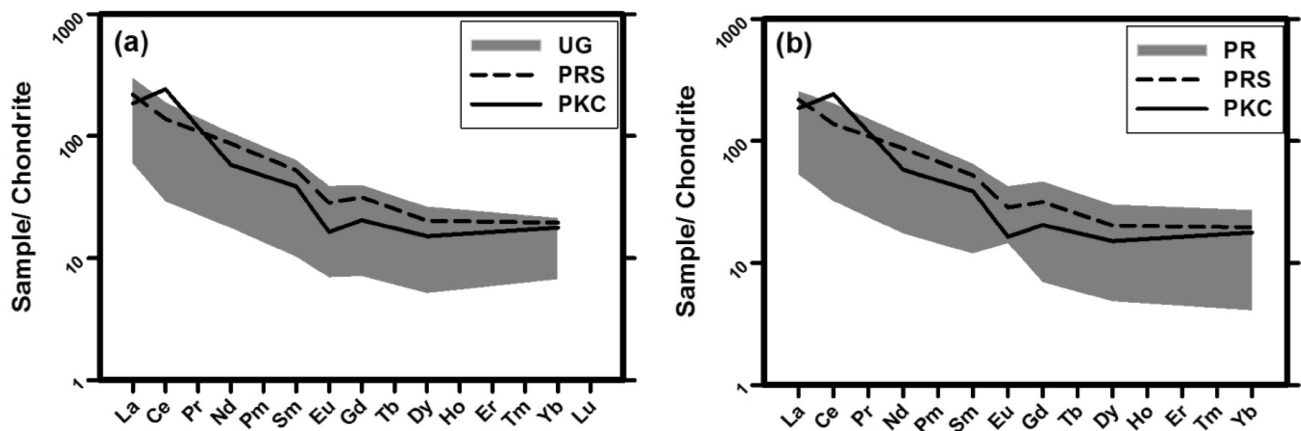
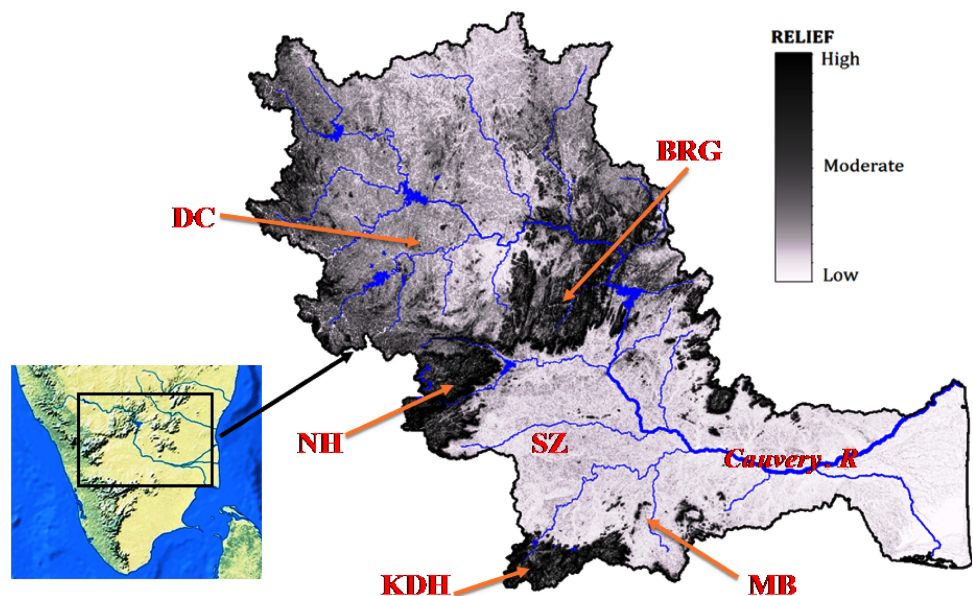


Fig. 8 The chondrite-normalized value of studied sediments from **a** Uttrangudi core (shaded area) and **b** Porayar core (shaded area) with plots of representative samples from the bordering SW margin of Cauvery Delta Territory rocks from Cauvery basin. PRS (Lateritic cover) and PKC (Mudstone)

Fig. 9 Shaded relief image of Cauvery basin southern India showing the distribution of major charnockite massifs. The different crustal blocks shown are Dharwar Craton (DC), Nilgiri Hills (NH), Biligirirangan Hills (BRG), Shear Zone (SZ), Kodaikanal Hills (KDH) and Madurai Block (MB)



charnockites in Palani and Kodaikanal hill areas. The other dominant lithologies of this region are migmatitic gneisses and migmatized charnockite along the shear zones. In its middle east-flowing track the main river is joined from the south by another major tributary, the Amravati River. It originates in the Palani and Kodaikanal hills and flows over the shear zone of the Madurai Block domain before joining the mainstream Cauvery River. On comparing, the chondrite-normalized REE plot of studied samples shows close resemblance with that of the charnockites from Kodaikanal and Palani hill region. The chondrite-normalized REE plot of charnockites from this region shows fractionation and Eu anomaly similar to the studied sediments (Figs. 6c and 7c). Similarly, the chondrite-normalized REE pattern and Eu anomaly of the migmatitic gneisses from this region resemble the sediments from both the cores (Figs. 6d and

7d). In the lower reaches, the Cauvery delta is bordered towards south-west by Tertiary rocks of Mio-Pliocene age. According to Ramasamy (2006), the upliftment along the western part of delta due to various tectonic activities has led to migration of Cauvery River from south to north which may have led the transportation of sediments from this uplifted region to delta. It is interesting to note that the chondrite-normalized REE pattern of selected samples analyzed from this Tertiary exposure, located towards the south-west part of the delta, exhibit similar chondrite-normalized pattern and Eu anomaly similar to the studied sediments (Fig. 8). Their resemblance to the sediments from Uttrangudi location is more prominent. This infers that the source for Uttrangudi core was local and sediment supply from the upper catchment would have been minimal during the Pleistocene. Further, according to Banerjee

(2000) the lower sea level during the Pleistocene would have exposed the adjoining shelf region. Due to this, the supply of sediments from upper catchment to the Uttrangudi region would have been cut and it might have received sediments only from the erosion of the Tertiary rocks exposed towards the S/W of the delta.

Dhal et al. (2018) has studied two cores from the southern and central part of the Cauvery delta. Based on the ^9Be fraction (reactive + dissolved and paleo-denudation rates), they have concluded that the variation in rainfall during summer monsoon and NE monsoon have led to change in source of the sediments of two cores. Singh and Rajamani (2001a, b) while studying the floodplain sediments of Cauvery River stated that high standing hills of charnockites have been main source of sediments, because of their recent uplift and physical denudation. Similarly, Singh et al. (2008) while studying Ganga basin sediments have discussed the combined effects of rainfall and relief using Sr and Nd isotopes. They concluded that highest erosion rate in the Himalayan drainage of the Gandak basin is due to its high relief and intense rainfall in its headwaters. The high relief and intense precipitation over the headwater basins of the Gandak appears to drive the rapid and focused erosion of this basin. The upper catchment region comprising of DC has lower relief and forms a large plateau with gently undulating topography (Fig. 9). In contrast, the SGB region has high relief, particularly in the charnockitic region. The charnockites in SGB form highland massifs with high relief that may facilitate erosion. Thus, higher rainfall in shorter time periods along with higher relief in the SGB together may have resulted in higher erosion of the SGB rock in comparison to the DC where rainfall is comparatively less and occurs over a longer period in this area possessing gentle topography. The temporal variation in input from different parts of the granulite belt may be due to local variability in rainfall at different times as is common in monsoon fed areas. Hence, it looks that the sediment supply at Uttrangudi site was dominantly from the BRG and NHG domains. The contribution of the SZ/MB domain is observed to have mainly started towards the late Pleistocene and continued through the Holocene. In contrast, the contribution from DC has remained minimal for the entire period of sedimentation in the region.

6 Conclusions

We found that delta sediments had highly enriched LREE and flat HREE patterns and slightly negative to positive Eu anomaly, which suggests a source of dominant felsic composition. When compared with different rock types, the studied samples show more resemblance to Charnockitic

rocks from high standing Nilgiri and Biligirirangan hills. In addition, the migmatitic gneisses and charnockite from the NMB have also acted as the source rocks. There is also a probability of a local source in the form of Tertiary rocks for the Uttrangudi sediments. The increased input from this region may be due to the uplift caused by tectonic activity and the lowering of sea level during the Pleistocene. Furthermore, the difference in the relief and amount and distribution of the rainfall had dominantly controlled the sediment supply from the source regions.

Acknowledgements We thank DST, New Delhi for financial assistance in form of a research grant (No. SR/S4/ES-21/Cauvery/P1) to P.S and JRF/SRF to M.Z.A. and analytical support from DST FIST Facility to the Department of Earth Sciences, Pondicherry University, Puducherry. The authors thank the anonymous reviewer for his constructive and helpful comments which highly improved this manuscript. The first author is thankful to Dr. Akhtar R. Mir and Dr. Farooq A. Dar for their assistance during preparation of this manuscript.

Compliance with ethical standards

Conflict of interest On behalf of the authors, the corresponding author states that there is no conflict of interest.

References

- Abedini A, Calagari AA (2015) Rare earth element geochemistry of the upper permian limestone: the Kanigorgeh mining district, NW Iran. *Turkish J Earth Sci* 24:365–382
- Abedini A, Rezaei AM, Calagari AA (2018) Lanthanide tetrad effect in limestone: a tool to environment analysis of the Ruteh Formation, NW Iran. *Acta Geodynamica et Geomaterialia* 15:229–246
- Alappat L, Tsukamoto S, Singh P, Srikanth D, Ramesh R, Frechen M (2010) Chronology of Cauvery delta sediments from shallow subsurface cores using high-temperature Post-IR IRSR dating of feldspar. *Geochronometria* 37:37–47
- Banerjee PK (2000) Holocene and Late Pleistocene relative sea level fluctuations along the east coast of India. *Mar Geol* 167:243–260
- Bhaskar RYJ, Naha K, Srinivasan R, Gopalan K (1991) Geology, geochemistry and geochronology of the Archean Peninsular Gneiss around Gorur, Hassan District, Karnataka, India. *Earth Planet Sci Lett* 100:399–412
- Bhatia MR, Crook KAW (1986) Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contrib Miner Petrol* 92:181–193
- Botsou F, Godelitsas A, Kaberi H, Mertzimekis TJ, Goettlicher J, Steininger R, Scoullou M (2015) Distribution and partitioning of major and trace elements in pyrite-bearing sediments of a Mediterranean coastal lagoon. *Chemie der Erde-Geochemistry* 752:219–236
- Brindley GW, Brown G (1980) Crystal structures of clay minerals and their X-ray identification. In: *The Mineralogical Society of Great Britain and Ireland*, London, vol 5, p 495
- Catlos JE, Kaan S, Poovalingam S, Chandra SD (2011) Geochemical and geochronological data from charnockites and anorthositic from India's Kodaikanal-Palani Massif, Southern Granulite Terrain, India. *Topics in Igneous Petrology*. Springer, Dordrecht, pp 383–417

- Chadwick B, Ramakrishnan M, Viswanatha MN (1981) Structural and metamorphic relations between Sargur and Dharwar supracrustal rocks and peninsular Gneisses in central Karnataka. *J Geol Soc India* 22:557–569
- Chadwick B, Vasudev VN, Hedge GV (2000) The Dharwar craton, southern India, interpreted as the result of Late Archean oblique convergence. *Precamb Res* 99:91–111
- Chakrapani GJ (2005) Factors controlling variations in river sediment loads. *Curr Sci* 88:4–25
- Chu ZX, Sun XG, Zhai SK, Xu KH (2006) Changing pattern of accretion/erosion of the modern Yellow River (Huanghe) subaerial delta, China: based on remote sensing images. *Mar Geol* 227:13–30
- Cullers RL (1994) The controls on the major and trace element variations of shales, siltstones, and sandstones of Pennsylvanian–Permian age from uplifted continental blocks in Colorado to platform sediment in Kansas, USA. *Geochim et Cosmochim Acta* 58:4955–4972
- Dhal SP, Balakrishnan S, Kumar P, Singh P, Sharan A, Chopra S (2018) $^{10}\text{Be}/^9\text{Be}$ ratios of Cauvery river delta sediments, southern India: implications for palaeo-denudation rates in the catchment and variation in summer monsoon rainfall during Late Quaternary. *Curr Sci* 115(9):1770
- Divakar Rao V, Subba Rao MV, Murthy NN (1999) Granite forming events and their role in crust formation of the Indian shield. *Revista Brasileira de Geociencias* 291:33–40
- Dou Y, Yang S, Shi X, Clift PD, Liu S, Liu J, Li C, Bi L, Zhao Y (2016) Provenance weathering and erosion records in southern Okinawa Trough sediments since 28 ka: geochemical and Sr–Nd–Pb isotopic evidences. *Chem Geol* 425:93–109
- Fralick PN, Kronberg BI (1997) Geochemical discrimination of clastic sedimentary rock sources. *Sed Geol* 113:111–124
- Garzanti E, Resentini A (2016) Provenance control on chemical indices of weathering Taiwan river sands. *Sed Geol* 336:81–95
- McLennan SM (1989) Rare earth elements in sedimentary rocks: influences of provenance and sedimentary processes. *Rev Mineral* 21:169–200
- Meen JK, Rogers JJW, Fullagar PD (1992) Lead isotopic compositions of the western Dharwar Craton, southern India: evidence for distinct middle Archean terranes in a late Archean craton. *Geochim et Cosmochim Acta* 56:2455–2470
- Meijerink AMJ (1971) Reconnaissance survey of the quaternary geology of Cauvery delta. *J Geol Soc India* 12:113–124
- Meissner B, Deters P, Srikanthappa C, Kohler H (2001) Geochronological evolution of the Moyar, Bhavani and Palghat shear zones of southern India: implication of east Gondwana correlations. *Precamb Res* 114:149–175
- Mir AR (2015) Rare earth element geochemistry of Post- to Neoarchean shales from Singhbhum mobile belt, Eastern India: implications for tectonic setting and paleo-oxidation conditions. *Chin J Geochem* 34(3):401–409
- Mir AR, Zubair AB, Shabber H, Balaram V (2015) Geochemistry of black shales from Singhbhum mobile belt, Eastern India: implications for paleo-weathering and provenance. *Him Geol* 36(2):126–133
- Mir AR, Balaram V, Javid AG, Shamim AD, Krishna AK (2016) Geochemistry of sedimentary rocks from Permian–Triassic boundary sections of Tethys Himalaya: implications for paleo-weathering, provenance, and tectonic setting. *Acta Geochim* 35(4):428–436
- Nesbitt HW, Young GM (1996) Petrogenesis of sediments in the absence of chemical weathering: effects of abrasion and sorting on bulk composition and mineralogy. *Sedimentology* 43:341–358
- Nesse WD (2000) *Introduction to Mineralogy*. Oxford University Press, New York, p 442
- Pattanaik JK, Balakrishnan S, Bhutani R, Singh P (2013) Estimation of weathering rates and CO_2 drawdown based on solute load: significance of granulites and gneisses dominated weathering in the Kaveri River basin, Southern India. *Geochim et Cosmochim Acta* 121:611–636
- Peucat JJ, Mahabaleswar B, Jayananda M (1993) Age of younger tonalitic magmatism and granulitic metamorphism in the south Indian transition zone (Krishnagiri area). *J Metamorph Geol* 11:879–888
- Plavsa D, Collins AS, Foden JF, Kropinski L, Santosh M, Chetty TRK, Clark C (2012) Delineating crustal domains in Peninsular India: age and chemistry of Block orthopyroxene-bearing felsic gneisses in the Madurai. *Precamb Res* 198:77–93
- Raith MM, Srikanthappa C, Dieter B, Hermann K (1999) The Nilgiri Enderbites South India: nature and constraints on protolith formation, high grade metamorphism and cooling history. *Precamb Res* 98:129–150
- Rajesh HM (2012) A geochemical perspective on charnockite magmatism in Peninsular India. *Geosci Front* 3:773–788
- Ramasamy SM (2006) Holocene tectonics revealed by Tamil Nadu Deltas, India. *J Geol Soc India* 67(5):637–648
- Santosh M, Maruyama S, Sato K (2009) Anatomy of a cambrian suture in Gondwana: Pacific-type orogeny in southern India? *Gond Res* 16(2):321–341
- Shapiro L, Brannock WW (1962) Rapid analysis of silicate, carbonate, and phosphate rocks. United States. *Geol Sur Bull* 1144A:1–56
- Sharma A, Rajamani V (2000) Major element, REE, and other trace element behavior in amphibolite weathering under semiarid conditions in southern India. *J Geol* 108:487–496
- Singh P (2009) Major, trace and REE geochemistry of the Ganga River sediments: influence of provenance and sedimentary processes. *Chem Geol* 266:242–255
- Singh P, Rajamani V (2001a) Geochemistry of the Kaveri flood plain sediments, Southern India. *J Sed Res* 711:50–60
- Singh P, Rajamani V (2001b) REE Geochemistry of recent clastic sediments from the Kaveri floodplains, southern India: implication to source area weathering and sedimentary processes. *Geochim et Cosmochim Acta* 65:3093–3108
- Singh SK, Rai SK, Krishnaswami S (2008) Sr and Nd isotopes in river sediments from the Ganga Basin: sediment provenance and spatial variability in physical erosion. *J Geophys Res Earth Surf* 113:F3006
- Singh P, Yadava MG, Malik ZA, Mohapatra PP, Laskar AH, Doradla S, Saravananavel J, Kumanan CJ (2015) Fertile farmlands in Cauvery delta: evolution through LGM. *Curr Sci* 108:218–225
- Srikanth D (2012) Geochemical and Carbon isotope studies on the surface and subsurface sediments of Cauvery Delta, South India. Unpub. Ph.D. Thesis, Pondicherry University, Pondicherry
- Swaminath J, Ramakrishnan M, Viswanatha MN (1976) Dharwar stratigraphic model and Karnataka craton evolution. *Rec Geol Surv India* 107:149–175
- Ta TKO, Nguyen VL, Tateishi M, Kobayashi I, Tanabe S, Saito Y (2002) Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. *Quat Sci Rev* 21:1807–1819
- Taylor SR, McLennan SM (1985) *The continental crust: its composition and evolution*. Blackwells, Oxford, p 312
- Tripathi JK, Rajamani V (1999) Geochemistry of the loessic sediments on Delhi ridge, eastern Thar desert, Rajasthan: implications for exogenic processes. *Chem Geol* 155:265–278
- Tripathi JK, Rajamani V (2007) Geochemistry and origin of ferruginous nodules in weathered granodioritic gneisses, Mysore Plateau, Southern India. *Geochim et Cosmochim Acta* 717:1674–1688

- Venkatesh B, Jose MK (2007) Identification of homogeneous rainfall regimes in parts of Western Ghats region of Karnataka. *J Earth Syst Sci* 116(4):321–329
- Wright LD (1977) Sediment transport and deposition at river mouths: a synthesis. *Geol Soc Am Bull* 88:857–868
- Yang XP, Liu YS, Li CZ (2007) Rare earth elements of Aeolian deposits in Northern China and their implications for determining the provenance of dust storms in Beijing. *Geomorphology* 87:365–377