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Textural and geochemical characteristics of sediments in and around Puttetti, Kanyakumari district, Tamil Nadu, India: Clues to weathering and environment

Athira Aji [1], N. Shinu [1,*], Anjana A.V. Panicker [1], Pavithra Saji S. [1], Lasitha S. [2]

[1] *Department of Geology, University College, Thiruvananthapuram, Kerala, India*
[2] *Department of Earth Sciences, Pondicherry University, Pondicherry, India*

ABSTRACT

Sediment samples collected from the areas in and around the Puttetti igneous suite were studied for their grain size and geochemical composition to determine the intensity of weathering and provenance. The method adopted for determining grain size is dry sieving through the vibratory sieve shaking method. Most of the samples consist of coarse sand to very fine sand, which is moderately well sorted to poorly sorted. This kind of grain size and sorting reveals variable current velocities and turbulence prevailed during the deposition, and the sediments might have been derived from different sources. The fine-skewed nature of sediments suggests the addition or removal of particles, while variations in kurtosis indicate that sorting may have occurred in high-energy environments and changes in transport and deposition mechanisms. Geochemical analysis for both major and trace elements was done since it provides valuable information about the provenance and transportation processes. It is observed that the concentration of silica is very high and is beyond the calibration range. From the correlation matrix, it is noted that the silica is negatively correlated to P_2O_5, MgO, Fe_2O_3, Al_2O_3, Sr, Cr etc., indicating a possible presence of a felsic suite of rocks in the provenance. The distributions of Na, K, Ca, Mg, Fe, and Mn are also discussed to provide insight into the physicochemical conditions of the depositional environment. The Al_2O_3/TiO_2 ratio suggests a mafic to felsic igneous source, while the Cu/Zn ratio indicates oxidising conditions during sedimentation.

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1. Introduction

Sediment texture, defined by grain relationships and size distribution, reveals valuable insights into the geological history and evolution of sedimentary basins, including energy conditions, depositional processes, transport mode, and distance (Sharath et al., 2022). The understanding of sedimentary processes provides valuable information about the factors that influence weathering, transportation, deposition, and is crucial in determining the source and reconstructing the environment of deposition (Omotoye et al., 2016). Sedimentologists have widely used grain size distribution analysis to classify sedimentary environments and elucidate the transport dynamics. The physical interpretation of the shape and structure

*Corresponding author. Email: nshinu@universitycollege.ac.in (NS), ajiathira66@gmail.com (AA), anjanapanicker@universitycollege.ac.in (AAVP), pavisalini01@gmail.com (PSS), lasitha_s@yahoo.com (LS)

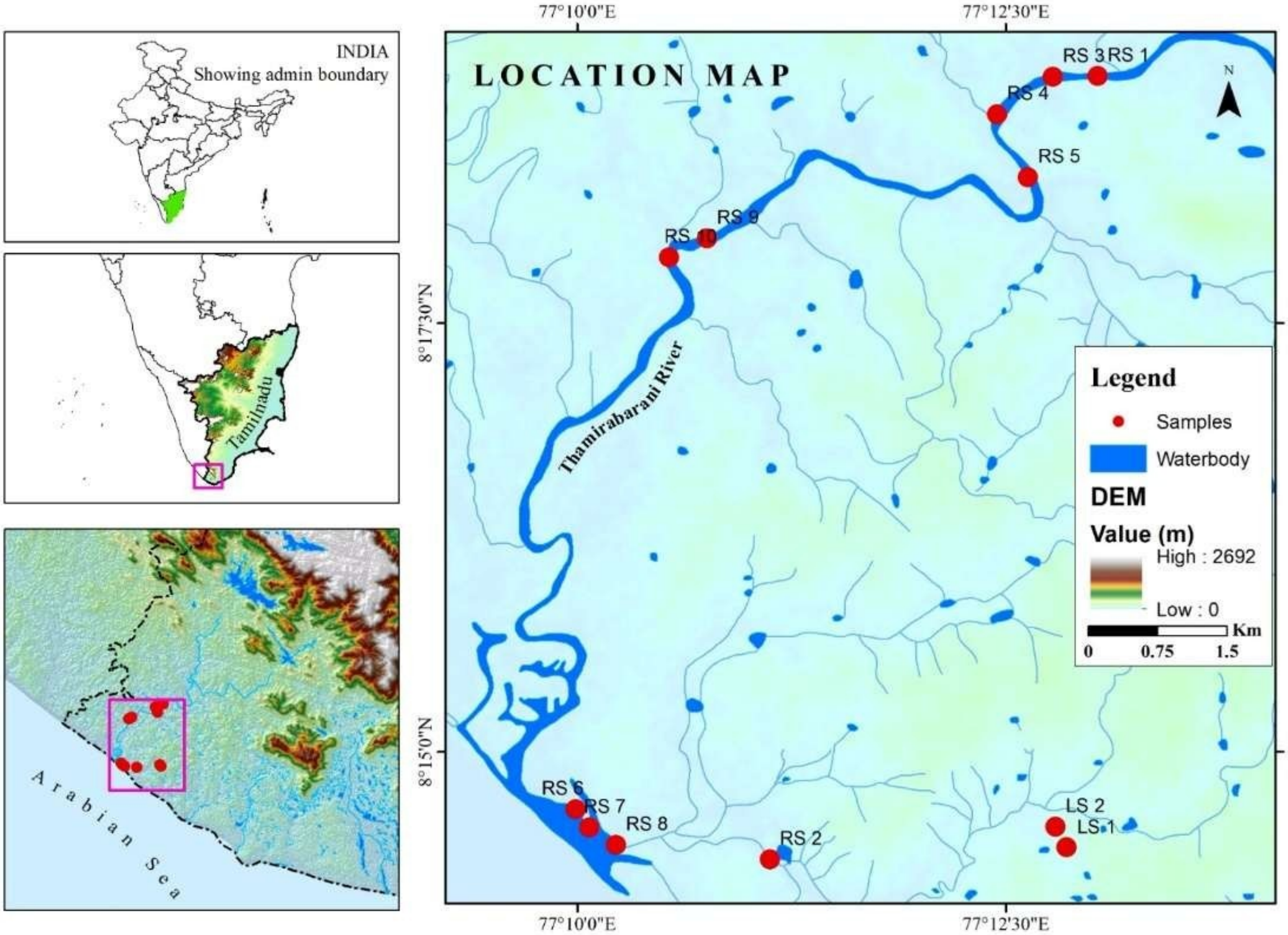

Fig. 1. Location map of the study area, Puttetti, Kanyakumari District, Tamil Nadu.

of clastic grain properties can be derived from estimated statistical parameters using several empirical relationships available in the literature (e.g., Krumbein and Pettijohn, 1938; Folk and Ward, 1957). The various attributes of grain size distribution are generally expressed by studying the Mean, Sorting, or dispersion of the values about the mean, i.e. Standard deviation, Symmetry (Skewness) and Peakedness (Kurtosis). Statistical parameters such as skewness and kurtosis provide insights into the normality and symmetry of grain size distributions within geological environments (Folk and Ward, 1957). Additionally, the geochemical composition of clastic sediments is widely used to infer sediment provenance (Varga et al., 2017), assess the weathering history of the source area (Ma et al., 2017), and interpret the tectonic setting (Verma and Armstrong-Altrin, 2013, 2016). The geochemical characteristics of sedimentary formations—particularly those associated with sands from beach, alluvial, and marine aeolian environments—also support interpretations of sand maturity and depositional processes (Juan and Hugo, 2007). The elemental concentrations in different grain sizes are primarily influenced by the composition and textural characteristics of the source rock. The geochemical features of sediments are capable of determining the distribution of trace metals in the sediments and discovering any correlation. The primary goals of this study are to ascertain the composition and textural characteristics of the sediments' grain sizes, assess the chemical components that make up the sediments, and look into the degree of chemical weathering and provenance of Puttetti area in Kanyakumari district, Tamil Nadu.

The Puttetti Alkaline Suite, located near Karungal in the Kanyakumari district of Tamil Nadu, is a geologically significant feature of South India (Fig. 1). This intrusive body, trending NNW-SSE, cuts through surrounding granulites and gneisses and consists of two distinct members: syenite and pyroxenite. Although these rocks are derived from a single parental magma, they display notable textural and compositional variations, even within the same exposure. It is believed that the Puttetti pluton formed from a single magma that split into two immiscible fractions, resulting in the formation of syenite and pyroxenite magmas (Rajesh, 1999, 2000). Situated south of the Achankovil Shear Zone in the Southern Granulite Terrain, the Puttetti Intrusive Suite is recognized for its unique characteristics, including the presence of zircon megacrysts and various sulphides and oxides (Parthasarathy and Sankar Das, 1976; Odom, 1982; Miyazaki and Santosh, 2005; Santosh et al., 1989). The proportion of pyroxene in syenite varies significantly, which earlier researchers attributed to the liquid immiscibility of a single magma (Rajesh, 1999, 2000). The Puttetti Igneous Suite (PIS) holds considerable geological significance, offering important insights into the tectonic evolution of the Southern Granulite Terrain. The suite's rocks are rich in alkalinity and incompatible elements, suggesting they originated from a mantle plume. This implies that the region experienced substantial volcanic and tectonic activity during the Neoproterozoic era, enhancing our understanding of Earth's mantle and crustal processes. In addition to its scientific value, the suite holds economic potential due to its richness in rare earth elements (REE) and uranium, making it an attractive target for mineral exploration and extraction. The Puttetti Alkaline Suite is a typical example of alkaline plutons of Pan African age (U-Pb zircon age of 580 Ma, Odom, 1982, Rajesh, 2003), located within South India's Trivandrum Block. The syenite body is a massive, medium- to coarse-grained, greenish-grey rock, predominantly composed of alkali feldspar and pyroxene, with smaller amounts of hornblende and biotite (Rajesh, 1999, 2000, 2003).

2. Materials and Methods

Sediment samples were collected from the nearby areas of the igneous suite, as well as from the small rivers, and also from Tamirabarani Ar for the present study. A field study was conducted during the first week of April 2024 to collect sediment samples from the Puttetti Igneous Suite and its surrounding areas. Twelve surface sediment samples were collected, including two land samples, nine river samples, and one beach sample. Alluvial samples were taken from small rivulets near the Puttetti Igneous Suite and from Kuzhithurai Ar, while the beach sample was collected from the river mouth near Thengapattanam. Sampling sites were chosen to cover both upstream and downstream sections of the Puttetti Igneous Suite. A 20 cm long PVC pipe was submerged in the water bodies to gather sediments, which were then sealed with a lid and transferred into a polythene bag. In addition, a 30 cm x 30 cm area was identified, and surface sediments were scraped to a depth of 2 cm.

The land samples were collected after removing a few inches of sediments from the surface layer to prevent any contamination. Nearly 1 kg of sample was collected in a polythene bag and was dried in the sunlight. After the removal of moisture from the samples, they were processed for sieve analysis and geochemistry. Before grain size analysis, the samples were treated with diluted HCl and H_2O_2 to remove carbonates and organic matter, and the grain size fractions were determined by dry sieving. Excess acid was removed from the beaker via repeated washing. The ASTM sieves method was adopted for this study. For sieve analysis, a representative sample of 80 g was taken after coning and quartering. Sieve analysis is carried out using the eight ASTM sieves 20, 30, 45, 60, 80, 120, 170, 230. ASTM sieve number 10), i.e., sand/gravel /boulder, was not used as gravel-sized sediments are absent. The scheme followed is the Udden-Wentworth Grade Scale (Folk, 1964).

For geochemical analysis, the samples were further dried and powdered using an agate mortar. Loss on Ignition (LOI) has been for about 4.5 gm of the powdered sample and is a very simple method for eliminating the carbonate and organic matter content in the sediments. Later, these samples were sprinkled over the aluminium cup of 40 mm filled with boric acid crystals.

For determining the major and trace elements, about 1–2 g of fine powder were spread over collapsible aluminium cups filled with boric acid and pressed at 40 tons for 30 s in a hydraulic pellet pressing machine. The pellet is marked at the bottom and ready for XRF analysis. Major elements were determined using a Bruker Pioneer Sequential wavelength dispersive X-ray spectrometer (Model S4), with ISO29581-2 as the standard. The analysis was conducted at the National Centre for Earth Science Laboratory (NCESS), Aakkulam, Thiruvananthapuram, India.

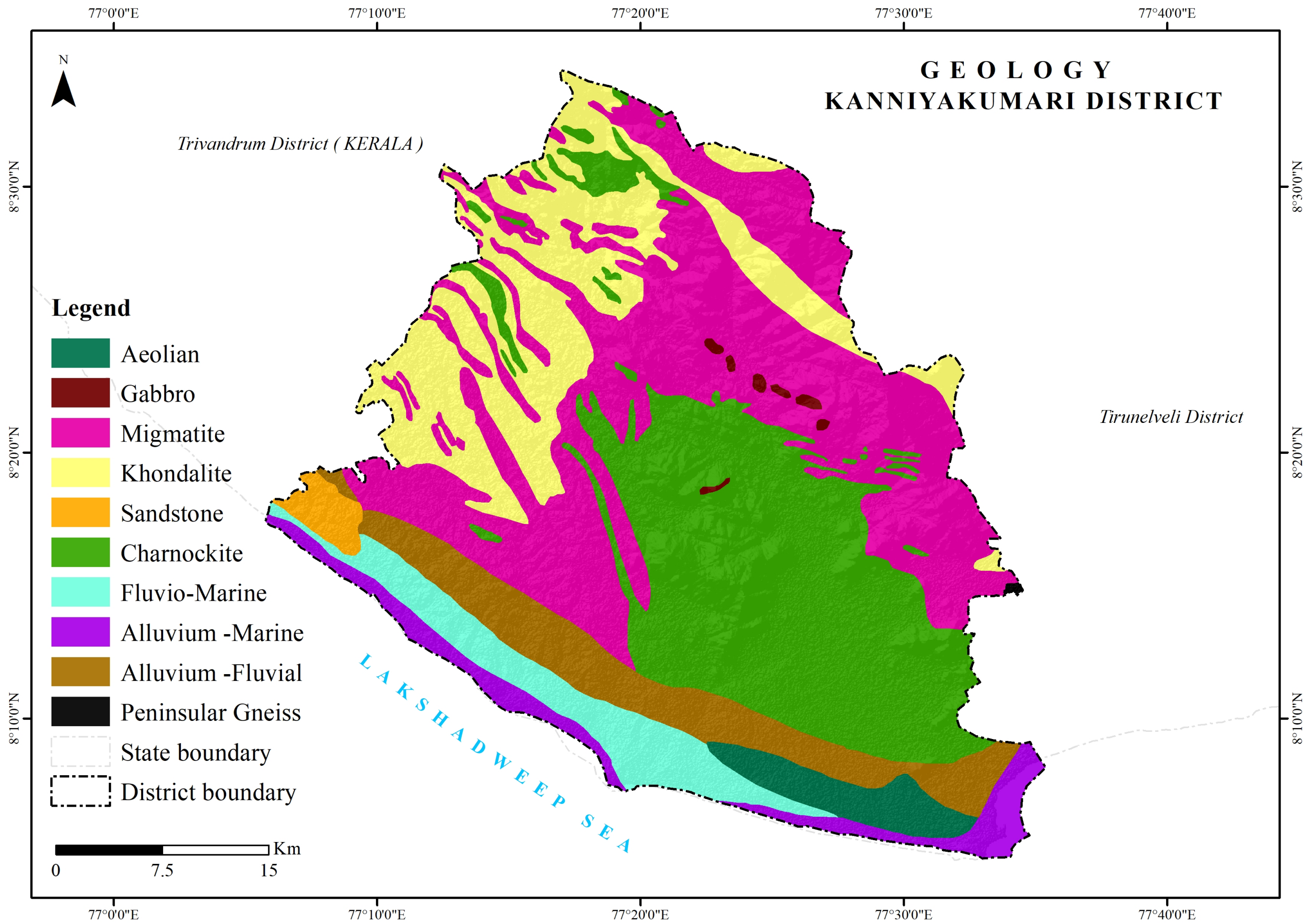

Fig. 2. Geological map of Kanyakumari district, Tamil Nadu (Modified after Raja et al., 2021).

For all elements, laboratory precision is better than 5%.

3. Results

Textural analysis involves measuring the different size fractions of sediment. Various methods are used to study sediment size and texture, and in this study, the dry sieving method was applied. The mean value indicates the average grain size and reflects the central point of the size distribution (Inman, 1952). Sorting is the second parameter, showing how uniform the grain sizes are. Skewness measures the asymmetry of the size distribution, while kurtosis indicates how peaked or flat the distribution is.

Skewness and kurtosis are especially useful for identifying sedimentary environments and determining the origin of the sediments (Ruiz-Martínez et al., 2016). For the present study, the results obtained from dry sieve analysis were used to generate various textural parameters such as Graphic Mean, Skewness, Kurtosis and Standard Deviation by employing graphical and statistical methods (Table 1, Fig. 3). In the present study, mean size (Mz) ranges from 0.167 to 1.13 phi with an average of 0.65 phi, which indicates that the sediments are of coarse sand to very fine sand category and are deposited under medium to high energy conditions. Standard deviation of the samples ranges from 0.28 to 1.05, representing well-sorted to moderately sorted sediments, and is indicative of variable current velocities and turbulence prevailing during deposition. The values of skewness vary from -0.15476 to 1 with an average of 0.5476, representing a coarse-skewed to very fine-skewed nature. The introduction of fine materials or removal of coarse fraction or winnowing action of sediments results in the formation of fine-skewed sediments (Friedman, 1967; Duane, 1964). The majority of the samples exhibit very fine skewness, which can be attributed to the unidirectional flow of the transporting

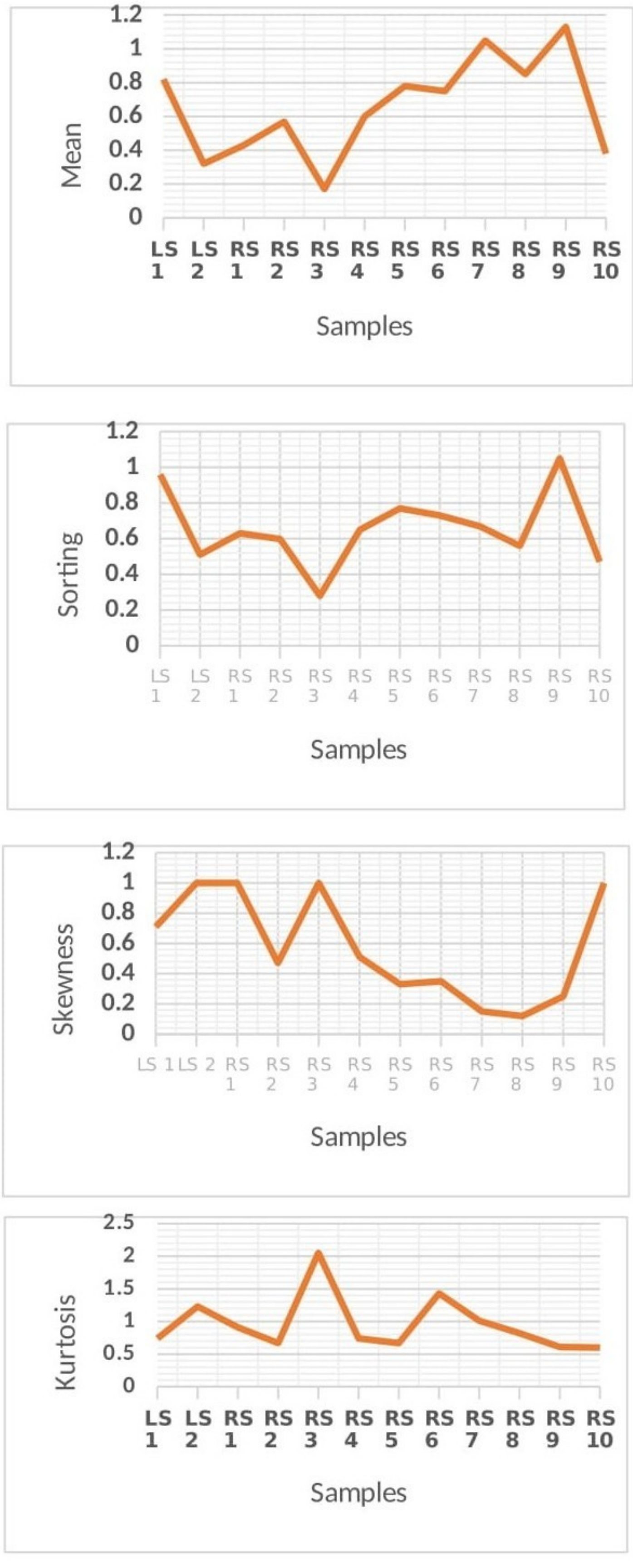

Fig. 3. The spatial variation of textural parameters of samples (Mean, Sorting, Skewness, Kurtosis).

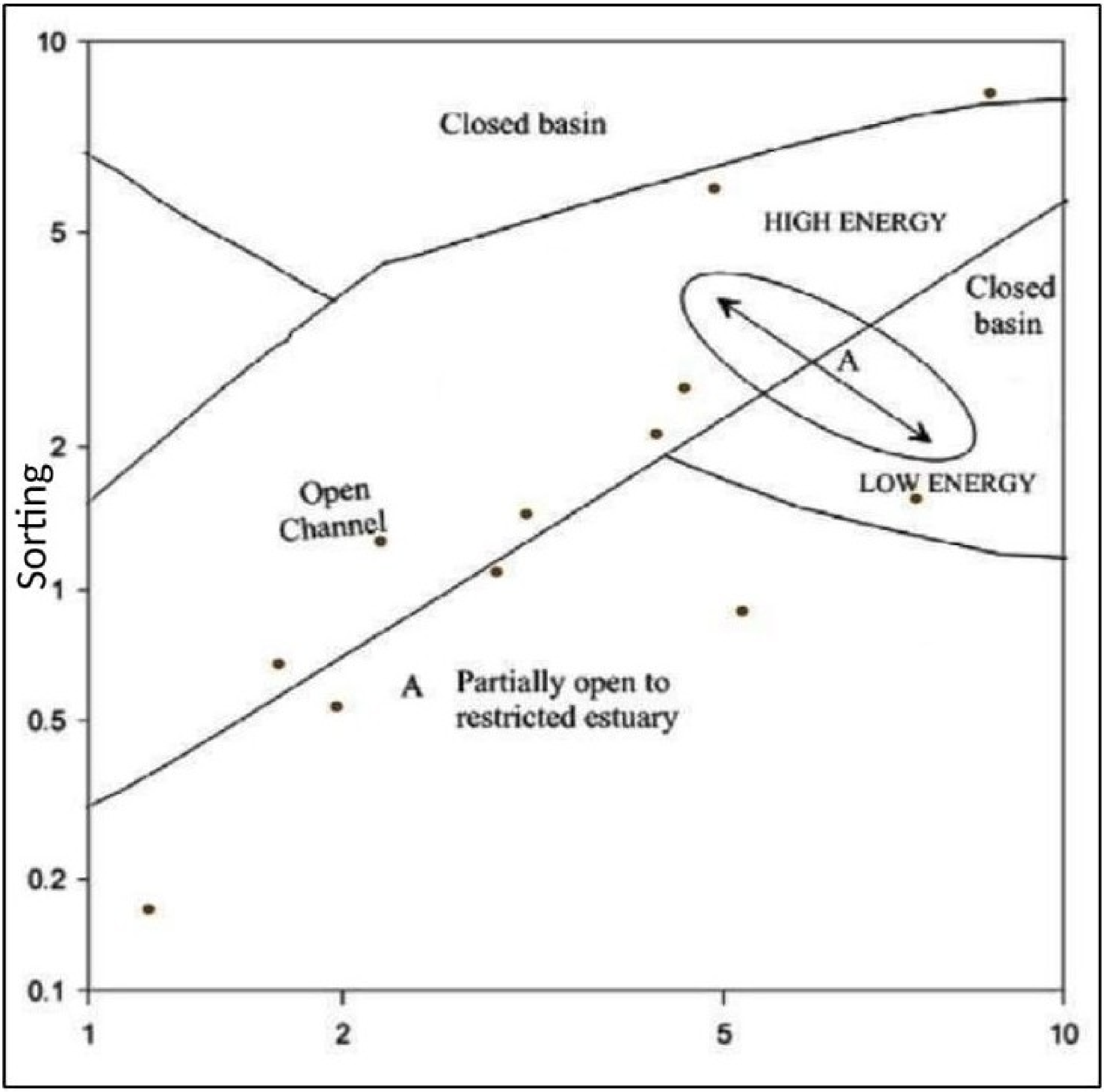

Fig. 4. Bivariate plot of mean grain size (X-axis) against sorting of sediments (Y-axis) (after Tanner, 1991).

agent accompanied by significant energy dissipation. The samples fall under the very platykurtic to very leptokurtic category, and this variation suggests sorting happened elsewhere in high-energy conditions and is indicative of transportational/depositional mechanisms between the locations (Srinivas et al., 2017). Kurtosis is not sensitive to the environment but provides a degree of peakedness. Tanner's plot is a correlation between mean and sorting, proposed by Tanner (1991) to understand the distinct environment in an area. For the present study, the majority of the samples fall in the area of fluvial and storm episodes in open channels, indicating high energy conditions of deposition, except two samples, which are deposited in closed basins in a relatively low energy environment (Fig. 4).

Table 1. The textural parameters of sediments in the study area.

SI No	Sample	Mean (ϕ)	Sorting (ϕ)	Sorting Type	Skewness	Skewness Type	Kurtosis	Kurtosis Type	Coarse Sand (%)	Medium Sand (%)	Fine sand (%)	Very fine sand (%)
1	LS 1	0.82	0.96	Moderately sorted	0.71	Very fine skewed	0.74	Platykurtic	61.5	24.35	13.71	4.21
2	LS 2	0.32	0.51	Moderately well sorted	1	Very fine skewed	1.23	Leptokurtic	79.3	16.98	3.82	0.17
3	RS 1	0.43	0.63	Moderately well sorted	1	Very fine skewed	0.91	Mesokurtic	71.52	24.84	4.39	-
4	RS 2	0.57	0.598	Moderately well sorted	0.47	Very fine skewed	0.67	Platykurtic	63.66	34.36	2.47	-
5	RS 3	0.17	0.28	Very well sorted	1	Very fine skewed	2.05	Very leptokurtic	90.09	10.01	0.14	-
6	RS 4	0.60	0.65	Moderately well sorted	0.51	Very fine skewed	0.74	Platykurtic	63.06	33.22	0.14	-
7	RS 5	0.78	0.77	Moderately sorted	0.33	Very fine skewed	0.67	Platykurtic	53.24	37.12	9.2	0.44
8	RS 6	0.75	0.73	Moderately sorted	0.35	Very fine skewed	1.43	Leptokurtic	54.31	38.97	6.62	0.09
9	RS 7	1.05	0.67	Moderately well sorted	0.15	Coarse skewed	1.01	Mesokurtic	32.71	60.65	6.52	0.11
10	RS 8	0.85	0.56	Moderately well sorted	0.12	Fine skewed	0.82	Platykurtic	44.8	53.6	1.85	-
11	RS 9	1.13	1.05	Poorly sorted	0.25	Fine skewed	0.61	Very platykurtic	43.12	31.14	21.12	4.61
12	RS 10	0.38	0.47	Well sorted	1	Very fine skewed	0.6	Very platykurtic	73.01	25.51	1.47	-

Table 2. Major element concentration (%) in samples.

Sample	SiO_2	TiO_2	Al_20_3	MnO	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	LOI	Total
LS1	57.58	0.51	14.79	0.13	4.99	4.24	1.79	8.26	6.62	0.18	0.69	99.78
LS2	62.18	0.61	12.70	0.08	6.87	2.58	1.44	5.83	5.25	0.21	2.01	99.76
RS1	75.58	0.76	6.92	0.06	9.37	0.97	0.81	1.38	0.80	0.19	2.87	99.71
RS2	84.72	0.89	5.30	0.03	5.20	0.42	0.62	0.81	0.25	0.13	1.45	99.82
RS3	75.46	0.67	7.17	0.04	9.72	0.61	0.59	0.82	0.90	0.19	3.70	99.87
RS4	84.50	0.48	6.29	0.03	4.15	0.62	0.57	1.04	1.11	0.11	1.01	99.91
RS5	79.72	0.76	7.45	0.05	5.28	1.46	1.02	1.40	1.67	0.17	0.83	99.81
RS6	86.62	1.06	5.73	0.02	3.42	0.46	0.79	0.76	0.52	0.10	0.37	99.85
RS7	84.45	0.61	5.13	0.02	3.41	2.56	0.57	0.50	0.43	0.10	2.08	99.86
RS8	84.70	0.45	4.84	0.02	2.98	3.43	0.55	0.54	0.35	0.10	1.85	99.81
RS9	78.75	1.44	8.84	0.04	4.66	0.84	1.29	1.43	1.63	0.13	0.69	99.74
RS10	82.82	0.69	6.76	0.04	4.86	0.71	0.85	1.17	1.26	0.11	0.61	99.88

Geochemical signatures of clastic sediments have been used to determine the provenance characteristics of the sediments. Several major oxide ratios are used for deciphering the provenance and depositional environment for sediments. The geochemical properties of river sediments are crucial for understanding various geological processes, such as element mobility, paleoenvironmental conditions, weathering intensity, and diagenetic changes occurring in a specific basin. (Taylor and McLennan, 1985; Condie et al., 1992; Singh, 2009; Ramos-Vázquez and Armstrong-Altrin, 2021; Nayak and Singh, 2022). The major elements analysed for the present study includes SiO_2, Al_2O_3, TiO_2, MnO, Fe_2O_3, CaO, MgO, Na_2O, K_2O, and P_2O_5. These oxides play a leading role in the earth's crust, inner spheres and that of the rock-forming minerals exposed on the surface. They are treated as indicators of the origin of primary minerals and their transformation in the geological environments over time. The sediments display notable variations in their bulk chemistry, reflecting the influence of various sedimentological factors. SiO_2 content of the samples ranges between 58 and 86%. TiO_2 and Al_2O_3 concentrations vary between 0.45 and 1.48% and 5.13 and 14.79%, respectively. The CaO content varies from 0.6 to 4.24%, while the Fe_2O_3 content ranges from 2.98 to 9.72%. The SiO_2 content of sediments showed positive correlation with Fe_2O_3, TiO_2 and CaO and negative correlation with Al_2O_3, K_2O, Na_2O, MgO, MnO and P_2O_5 (Table 2, 3, 4). The Al_2O_3 content of sediments showed positive correlation with Fe_2O_3, TiO_2, P_2O_5, CaO and Na_2O and negative correlation with SiO_2, K_2O, MgO and MnO (Table 4). We do not find any significant correlation between LOI and CIA values for the sediments.

Silica content is higher in most of the samples, especially in coarse to medium sand, compared to fine sand. In the present study area, the concentration of SiO_2 is weakly correlated with TiO_2. The negative correlation of SiO_2 with Al_2O_3, K_2O, Na_2O, MgO, MnO, and P_2O_5 is noted for the present study. Like igneous rocks, for the present study, also Al_2O_3 increases with decreasing Fe, Cr, and Mn. Al_2O_3 is positively correlated to K_2O, Na_2O, and MgO and is weakly correlated to Fe_2O_3, CaO, and P_2O_5. Al_2O_3 is positively correlated to K_2O. Average of the SiO_2/Al_2O_3 ratio is 11.72. Al_2O_3 vs TiO_2 ratio ranging from 5.40 to 29. Fe_2O_3 is positively correlated to Cr and MnO. Na_2O is positively correlated to K_2O and Al_2O_3. Na_2O/K_2O ratio varies from 0.84 to 3.24

Table 3. Trace element concentrations (ppm) and their ratios in samples.

Sample	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Ba	La	V/Cr	Cr/V	Cu/Zn	Rb/Sr
LS1	54	59	2	18	175	36	509	167	43	730	99	67	0.92	1.09	0.10	3.05
LS2	85	99	11	19	116	32	409	128	44	701	282	73	0.86	1.16	0.16	3.20
RS1	138	144	13	26	36	23	58	83	21	1248	375	80	0.96	1.04	0.72	0.70
RS2	157	78	ND	23	13	29	5	25	16	351	390	43	2.01	0.50	1.77	0.20
RS3	112	143	10	35	37	22	29	51	19	144	392	60	0.78	1.28	0.95	0.57
RS4	47	47	ND	27	16	25	40	69	17	117	397	16	1.00	1.00	1.69	0.58
RS5	119	57	21	25	39	25	59	76	21	138	320	32	2.09	0.48	0.64	0.78
RS6	199	45	ND	20	14	26	15	39	15	187	383	17	4.42	0.23	1.43	0.38
RS7	83	30	ND	26	9	20	31	151	16	200	285	7	2.77	0.36	2.89	0.21
RS8	40	19	ND	29	3	19	25	228	14	151	171	1	2.11	0.48	9.67	0.11
RS9	302	74	1	16	59	25	104	107	20	1019	369	61	4.08	0.25	0.27	0.97
RS10	102	43	ND	22	28	22	46	82	21	145	380	23	2.37	0.42	0.79	0.56

Table 4. Correlation matrix for major elements (%) in sediment samples.

	SiO_2	TiO_2	Al_20_3	MnO	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	LOI
SiO_2	1										
TiO_2	0.226	1									
Al_20_3	-0.957	-0.092	1								
MnO	-0.947	-0.231	0.937	1							
Fe_2O_3	-0.420	-0.028	0.227	0.316	1						
CaO	-0.571	-0.527	0.530	0.558	-0.254	1					
MgO	-0.845	0.141	0.944	0.870	0.066	0.485	1				
Na_2O	-0.937	-0.259	0.963	0.946	0.117	0.652	0.889	1			
K_2O	-0.937	-0.234	0.981	0.928	0.625	0.625	0.911	0.988	1		
P_2O_5	-0.799	-0.121	0.666	0.704	0.812	0.167	0.534	0.583	0.596	1	
LOI	-0.130	-0.306	-0.138	-0.066	0.731	-0.010	-0.357	-0.161	0.468	0.468	1

Table 5. Correlation matrix for trace elements (ppm) in sediment samples.

	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Ba	La
V	1											
Cr	0.220	1										
Ni	-0.333	0.144	1									
Cu	-0.452	0.240	0.500	1								
Zn	-0.124	0.209	-0.533	-0.518	1							
Ga	-0.009	0.140	-0.400	-0.622	0.828	1						
Rb	-0.248	0.102	-0.438	-0.523	0.972	0.821	1					
Sr	-0.441	-0.413	-0.574	-0.055	0.296	-0.068	0.402	1				
Y	-0.246	0.227	-0.291	-0.480	0.948	0.800	0.974	0.289	1			
Zr	0.410	0.533	-0.461	-0.470	0.484	0.351	0.424	0.106	0.428	1		
Ba	0.500	0.358	0.352	0.177	-0.587	-0.341	-0.656	-0.853	-0.529	-0.085	1	
La	0.275	0.829	-0.481	-0.257	0.656	0.553	0.553	-0.170	0.629	0.792	-0.085	1

with an average of 1.334. Low values of the MgO content are noted for the present study (Table 2 and Table 4). Trace elements (TE) are those elements that occur in a mineral in small amounts at less than 0.1 wt. The major trace elements selected for the present study include V, Cr, Cu, Ni, Zn, Rb, Sr, Zr, Ba etc. The concentration of Zn varies from 3 ppm to 175 ppm with an average of 45 ppm. The presence of Ni is absent or very less in sediments. Its concentration changes from 1 ppm to 21 ppm with an average of 11.6 ppm, and a weak correlation with Fe and Al is observed. Cr value in the study area ranges between 19 and 143, with an average of 69.8. In sediments, Cr may be present in primary detrital phases such as chromite, magnetite, and ilmenite. Sr exhibits a strong positive correlation with the CaO content. In the present study, the zircon concentration varies from 144 ppm to 1248 ppm with an average of 427.58 ppm. Rb/Sr ratio ranges from 0.2 to 3.19. A significant negative correlation between Rb and Sr is noted. This study's Cu/Zn ratio varies between 0.103 to 2.89 with an average of 1. In the present study, the V/Cr ratio ranges from 0.9 to 4 with a mean value of 1.91, indicating an oxic condition, while the Cr/V ratio ranges between 0.2 to 1.16 with a mean value of 0.71 (Table 3 and Table 5).

4. Discussion

Sediment characteristics are mainly influenced by the source rock type, climate, landscape, transport energy, and water movement in the river basin (Sensarma et al., 2008; Verma et al., 2012; Sharma et al., 2013). Among these, the source rock (lithology) plays the most important role in shaping the sediment's mineral content and chemical makeup (Sharma et al., 2013). Several major oxide ratios are used for deciphering the provenance and depositional environment of sediments. The geochemical properties of river sediments are crucial for understanding various geological processes, such as element mobility, paleoenvironmental conditions, weathering intensity, and diagenetic changes occurring in a specific basin. (Taylor and McLennan, 1985; Condie et al., 1992; Singh, 2009; Ramos-Vázquez and Armstrong-Altrin, 2021; Nayak and Singh, 2022). The major elements analysed for the present study includes SiO_2, Al_2O_3, TiO_2, MnO, Fe_2O_3, CaO, MgO, Na_2O, K_2O, and P_2O_5. The sediments display notable variations in their bulk chemistry, reflecting the influence of various sedimentological factors. SiO_2 content of the samples ranges between 58 and 86% and correspondingly lower concentration of other elements, because of their higher quartz content and silica dilution effect. The enrichment of SiO_2 in comparison to other major oxides suggests dilution of unstable oxides during weathering. The ratio of Al_2O_3/TiO_2 is considered a good indicator of provenance for sedimentary rocks, in particular, if the source is igneous (Hayashi et al., 1997). The Al_2O_3 vs TiO_2 ratio, ranging from 5.40 to 29 suggests the presence of intermediate to felsic igneous rocks in the province. These oxides play a leading role in the earth's crust, inner spheres and that of the rock-forming minerals exposed on the surface. They are treated as indicators of the origin of primary minerals and their transformation in the geological environments over time. TiO_2 and Al_2O_3 concentrations vary between 0.45 and 1.48% and 5.13 and 14.79%, respectively. The CaO content varies from 0.6 to 4.24.%, while the Fe_2O_3 content ranges from 2.98 to 9.72.%. The sediments of the present study have lower concentrations of MgO and P_2O_5 suggestive of intermediate to felsic provenance (Hayashi et al., 1997). The SiO_2 content of sediments showed positive correlation with Fe_2O_3, TiO_2 and CaO and negative correlation with Al_2O_3, K_2O, Na_2O, MgO, MnO and P_2O_5 (Table 4). The Al_2O_3 content of sediments showed positive correlation with Fe_2O_3, TiO_2, P_2O_5, CaO and Na_2O and negative correlation with SiO_2, K_2O, MgO and MnO. Sediments from Puttetti and surrounding areas contain SiO_2 as the most dominant oxide in the sediments, confirming the sandy nature of the sediments and its detrital origin.

Silica content is more in most of the samples especially in coarse to medium sand compared to fine sand. In the present study area, the concentration of SiO_2 is weakly correlated to TiO_2 indicating the presence of intermediate to felsic suite of rocks in the provenance (Hayashi et al., 1997). The negative correlation of SiO_2 with, Al_2O_3, K_2O, Na_2O, MgO, MnO and P_2O_5 suggests that grain size control on the geochemistry of these sediments. The alumina concentration is high in land samples compared to other samples indicating the presence of silicate minerals. Al_2O_3 concentrations in igneous rocks generally increases with decreasing Fe, Cr, and Mn content and similar trend is observed for the present study. Al_2O_3 is positively correlated to K_2O, Na_2O and MgO and is weakly correlated to Fe_2O_3, CaO and P_2O_5. Weak correlation in the case of Fe_2O_3 indicates that the presence of iron is mostly in the clays rather than in the form of iron minerals. Weak correlation with CaO suggests that it is hosted by carbonates rather than silicates. Al_2O_3 is positively correlated to K_2O, indicating the presence of potassium-bearing silicates such as K-feldspar, K-mica, etc. Average SiO_2/Al_2O_3 ratios (11.72) indicate a low to moderate degree of maturation of the sediments. Fe_2O_3 is positively correlated to Cr and MnO, indicating the possibility of precipitation of Fe^{3+} hydrous oxides formation as coatings on other mineral phases and coprecipitation of metals such as Mn, Cu, Co, Cr and many others in limonitic or hematitic phases (Kanhaiya et al., 2018). Na_2O is positively correlated to K_2O and Al_2O_3, which suggests that the origin of Na minerals is terrigenous. Na_2O/K_2O ratio varies from 0.84 to 3.24 with an average of 1.334, indicating a predominance of plagioclase over K-feldspar among feldspars. Even K-micas are identified in the coarse fraction (Ranjan and Banerjee, 2009). Low values of the MgO are consistent with the less dominance of clay minerals (Kanhaiya et al., 2018).

Trace elements (TE) are those elements that occur in sediments in small amounts at less than 0.1 wt. The main trace elements selected for the present study include V, Cr, Cu, Ni, Zn, Rb, Sr, Zr, Ba, etc. The concentration of Zn varies from 3 ppm to 175 ppm with an average of 45 ppm. The principal zinc carrier in mafic rocks is magnetite. The high Zn content in some samples may be due to anthropogenic activities such as agriculture (Kanhaiya et al., 2018). Zinc concentration is relatively high in samples in the vicinity of the igneous suite, while Ni is more or less absent in the majority of sediments. Its concentration changes from 1 ppm to 21 ppm with an average of 11.6 ppm. Ni is adsorbed by clay minerals or hydroxides of Fe and Mn, and a weak correlation among Al and Fe indicates the absence/removal of clay minerals and the possible presence of Ni in Fe-hydroxides rather than in aluminosilicates (Rajapaksha et al., 2012). Cr value in the study area ranges between 19 and 144, with an average of 69.8. Moderate Cr values in the present study area indicate the dominance of the felsic suite of rocks (Yellapa et al., 2019). The presence of chromium in sediments may be as chromite, magnetite, and ilmenite. Sr content is dominant in the sediments collected from the close vicinity of the alkali igneous suite. Sr exhibits a strong positive correlation with the CaO content in samples, probably due to their occurrence in multiple mineral phases, and is often related to the carbonate content (Du et al., 2021). The primary zircon of magmatic and peritectic

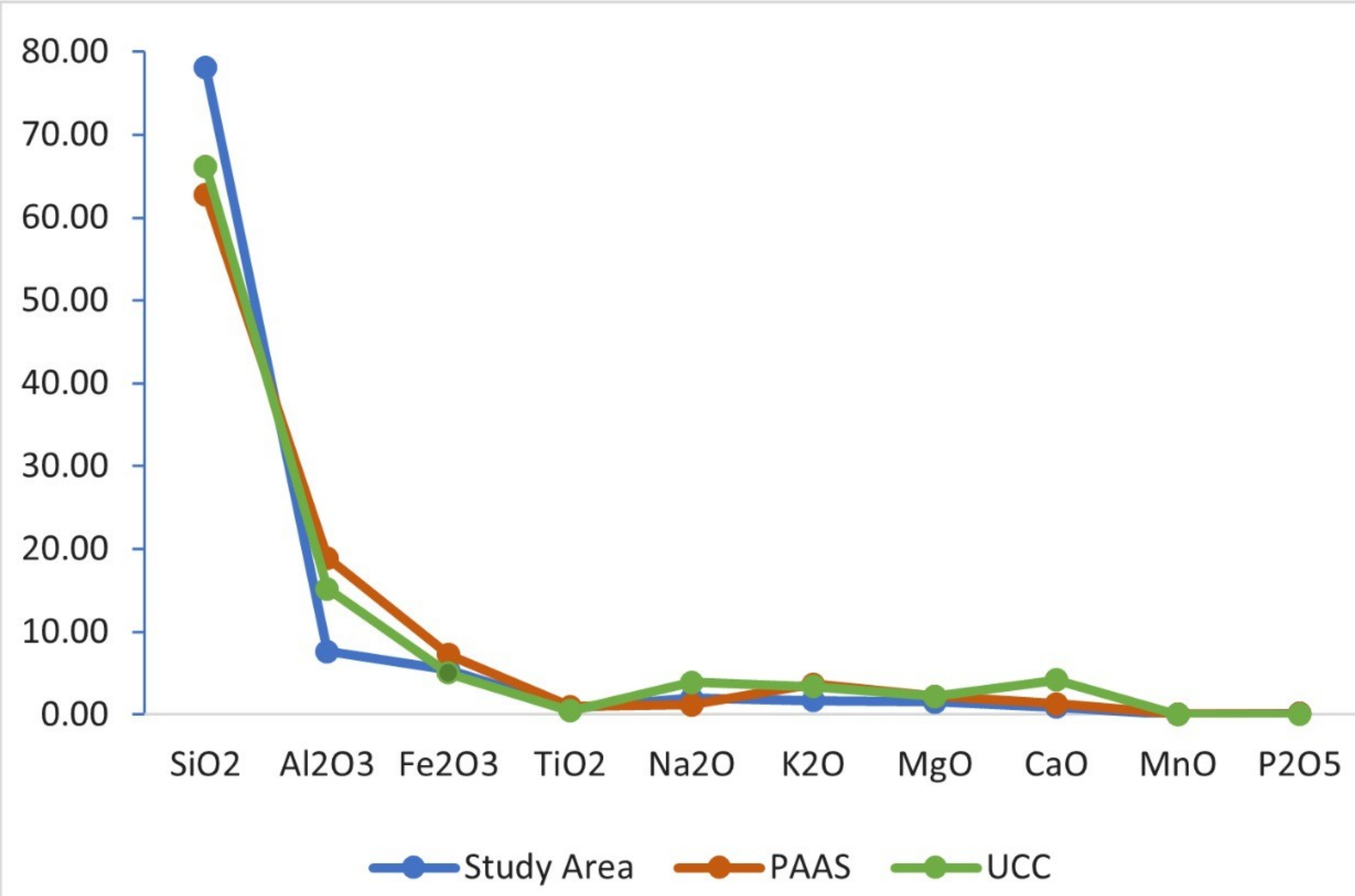

Fig. 5. Comparison of the major oxide data with global reference standards—Post-Archean Australian Shale (PAAS) and Upper Continental Crust (UCC).

origins is common not only in magmatic rocks of felsic composition but also in some mafic intrusives such as gabbro and pyroxenite. In the present study, the zircon concentration varies from 144 ppm to 1248 ppm, with an average of 427.58 ppm, and may be due to the proximity of the source rock, syenite, rich in zircon.

Rb/Sr ratio ranges from 0.2 to 3.19. Significant negative correlation between Rb/Sr suggests that the ratios are strongly affected by chemical weathering (Babu et al., 2025). High Rb/Sr ratios in sediments could be due to Rb-enriched rocks in the hinterland and chemical weathering. It has been reported that felsic granites and pegmatites contain Rb-enriched minerals (muscovite, albite, K-feldspar, and lepidolite and may have strong physical and chemical weathering (Soman, 2002). High Cu/Zn ratios imply reducing depositional conditions, whereas low Cu/Zn ratios suggest oxidising conditions (Hallberg, 1976; Saha et al., 2017; Liu et al., 2022, Zhang et al., 2024). In this study Cu/Zn ratio varies between 0.103 to 2.89 with an average of 1.03, indicating that the sediments were deposited under oxidising environments (Goldberg and Humayun, 2016). It is reported that Cu, Zn, and Pb were to some extent derived from multisource anthropogenic inputs besides geochemical background contributions by studying heavy metals in river sediments of Karnataka (Hejabi and Basavarajappa, 2012). The V/Cr ratio is considered as a good indicator of a redox condition; if this ratio is >4.5, which represents an anoxic condition, whereas <2 indicates an oxic condition in the depositional environment (Jones and Manning, 1994). In the present study, the V/Cr ratio ranges from 0.9 to 4, with a mean value of 1.91, indicating an oxic condition. The Cr/V ratio ranges between 0.2 and 1.16, with a mean value of 0.71, suggesting that the parent rock for the sediments may be felsic (Bhattacharya et al., 2012).

By comparison with the average Upper Continental Crust (UCC) and Post-Archean average Australian Shale (PAAS), representative of continentally derived sediments, the sediments from study area are enriched in SiO_2 but, are depleted in other major elements (Table 6 and Fig. 5). The average SiO_2 content

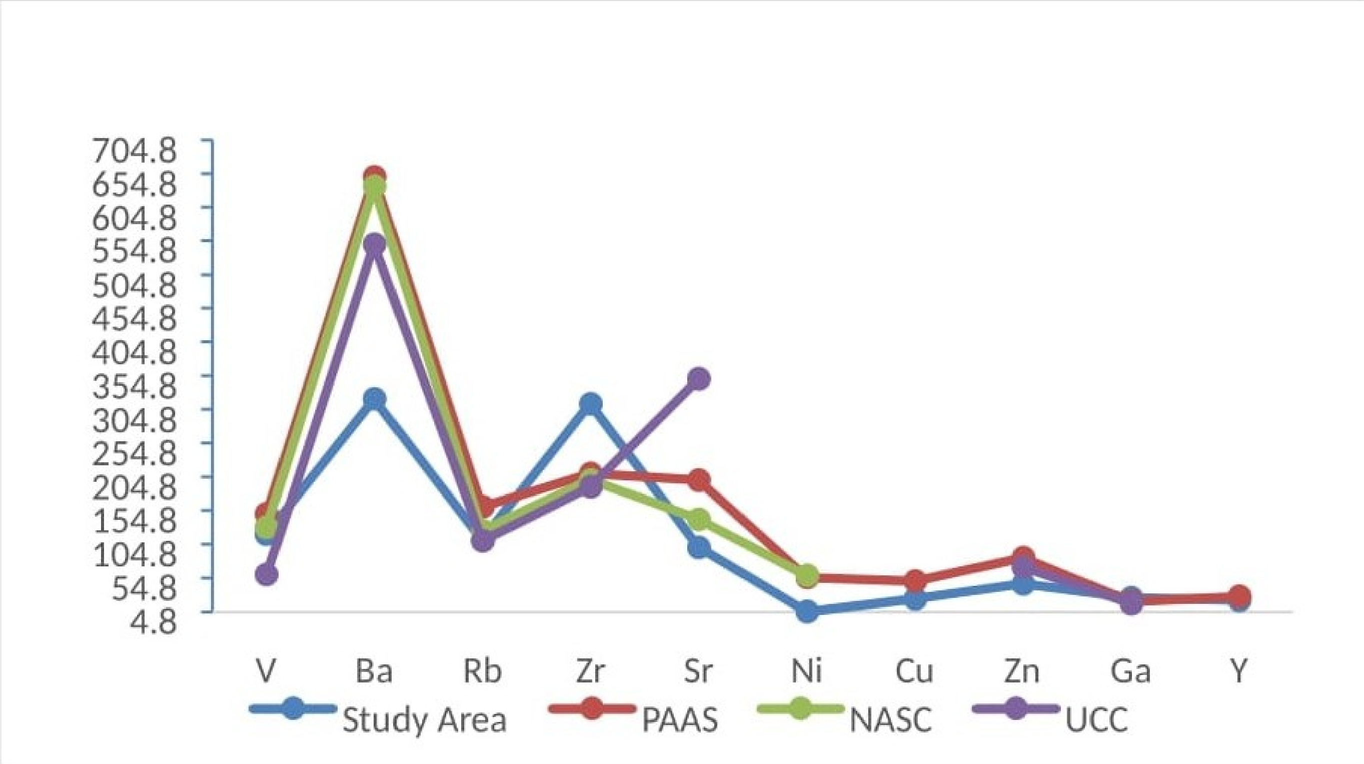

Fig. 6. Comparison of average trace element concentrations (in ppm) with global reference standards—Post-Archean Australian Shale (PAAS), Average North American Shale (NASC), and Upper Continental Crust (UCC).

of the sediments was much higher than in the UCC and PAAS. The average Al_2O_3 content was lower than that in UCC and PAAS. The average content of MgO, CaO, K_2O, and TiO_2 were lower in comparison with UCC and PAAS values. Average Fe_2O_3 content was much lower than PAAS but higher than that of UCC. The observed decline in MnO, CaO, and Na_2O is likely due to quartz dilution, but also indicates intense weathering and recycling of the studied sediments.

The content of Na_2O and K_2O is high only in land samples, and the low concentration of Na_2O and K_2O in the river sediments indicates a high-energy environment. The different major oxide ratios also indicate the provenance and environment of sediment deposition. Average SiO_2/Al_2O_3 ratios are low, indicating a low to moderate degree of maturation of the sediments. The Al_2O_3 vs TiO_2 ratio is used to determine the source rock and the presence of mafic to intermediate felsic igneous rocks in the province.

The total trace element content of the sediments varied widely from 700 ppm to 2245 ppm, with an average value of 1210.5 ppm. The sediments revealed that Sr, Rb, Zn, and Cu contents are lower in comparison with Average North American shale (NASC), PAAS, and UCC. The low values of these elements are due to the dilution effect because of the presence of a high amount of quartz in the sediments (Table 7 and Fig. 6).

Among the trace elements, the Cu, Ni, and Cr concentrations are noticeable both in land and sediment samples, and they may have originated from the igneous parent in the nearby region. Zr is concentrated in land samples (LS-1 and LS-2) and the river sediment (RS-1) nearer to the source and in the beach sample (RS-9). The high concentration in the first three situations indicates the proximity of the alkaline suite and in the fourth one by the selective concentration through coastal reworking in the river mouth near Thengapattanam and also may be due to the dumping of syenite rock masses as sea wall for the protection of beach from coastal erosion and its subsequent erosion and deposition may lead to the enrichment. Floyd et al. (1989) proposed that high Ti and Ni contents of sediments indicated a mafic rather than a felsic source rock, and Ryan and Williams (2007) found Ti a useful discriminator of tectonic setting. The wide range of Ni contents suggests that the Ni concentration may not be a robust indicator of source. High Cu/Zn ratios imply reducing deposi-

Table 6. Comparison of the data with global reference values, including Post-Archean Australian Shale (PAAS) and Upper Continental Crust (UCC).

Major (wt.%) oxides	Present study	Post-Archean Australian Shale (PAAS)	Upper Continental Crust (UCC)
SiO_2	78.09	62.80	66.20
Al_2O_3	7.66	18.90	15.20
Fe_2O_3	5.41	7.22	5.00
TiO_2	0.74	1.00	0.50
Na_2O	1.99	1.20	3.90
K_2O	1.70	3.70	3.40
P_2O_5	0.14	0.16	-
MnO	0.05	0.11	-
MgO	1.57	2.20	2.20
CaO	0.91	1.30	4.20

Table 7. Comparison of average trace element concentrations (in ppm) with Post-Archean Australian Shale (PAAS), Average North American Shale (NASC) and Upper Continental Crust (UCC).

Elements (ppm)	Present Study	Post-Archean Australian Shale (PAAS)	Average North American Shale (NASC)	Upper Continental Crust (UCC)
V	119.83	150	130	60
Ni	4.83	55	58	-
Cu	23.83	50	-	-
Zn	45.42	85	-	71
Ga	25.33	20	-	17
Rb	110.83	160	125	110.20
Sr	100.50	200	142	350
Y	21.33	27	-	22
Zr	313.42	210	200	190
Ba	320.25	650	636	550

tional conditions, and for the present study, the ratio indicates that the sediments were deposited under oxidising conditions.

5. Conclusions

The results and discussion of the present study led to the following conclusions:

a. The textural analysis carried out for the sediments in the different regions of the study area reveals a sandy texture.

b. Entire sediments are floored mainly of coarse sand to very fine sand, which is poorly sorted to moderately well sorted, indicating variable current velocities and turbulence prevailed during deposition, and are derived from different sources. The fine-skewed nature of sediments indicates the introduction of fine materials or the removal of coarse fractions. The variation in kurtosis suggests that part of the sediment achieved its sorting elsewhere in a high-energy environment, and it indicates a change in sediment transportation/depositional mechanism between the sampling locations.

c. Sediments from Puttetti and surrounding areas contain SiO_2 as the most dominant oxide in the sediments, confirming the sandy nature of the sediments and their detrital origin.

d. The sediments display notable variations in their bulk chemistry, reflecting the influence of various sedimentological factors. SiO_2 content of the samples ranges between 58 and 86% and correspondingly lower concentration of other elements, because of their higher quartz content and silica dilution effect. The enrichment of SiO_2 in comparison to other major oxides suggests dilution of unstable oxides during weathering.

e. The ratio of Al_2O_3/TiO_2 is considered a good indicator of provenance for sedimentary rocks, in particular, if the source is igneous (Hayashi et al., 1997). The Al_2O_3 vs TiO_2 ratio, ranging from 5.40 to 29, suggests the presence of intermediate to felsic igneous rocks in the province.

f. Rb/Sr ratio ranges from 0.2 to 3.19. Significant negative correlation between Rb/Sr suggests that the ratios are strongly affected by chemical weathering. High Rb/Sr ratios in sediments could be due to Rb-enriched rocks in the hinterland and chemical weathering.

g. The Cu/Zn ratio in this study varies between 0.103 to 2.89, with an average of 1.03, indicating that the sediments were deposited under oxidising environments.

h. The geochemical distributions of Na, K, Ca, Mg, Fe, and Mn from the bulk fraction are ascribed to the physicochemical conditions of the depositional environment. The oxide concentrations in the samples point to depositional environments of the sediments that graded from freshwater to a marine depositional environment; the sediments were deposited in an oxidising environment.

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Credit Statement

AA: Field work, Analysis, Methodology, Data generation. NS: Conceptualisation, Supervision, Methodology, Resources, Writing – original draft. AAVP: Writing – review & editing. PS: Field work, analysis assistance, LS: review and editing, figure preparation.

Conflict of interest

The authors declare that they have no known financial interests or personal relationships that could influence the work reported in this paper.

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