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Depositional environmental, provenance and climatic signatures of textural characteristics and heavy mineral distribution of the Vaigai river channel bed sediments, Southern India

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Abstract. Surface sediments of the river channels provide a proxy to understand contemporary-paleoconditions of sedimentary environments, climate, provenance, etc. Systematic field mapping, and delineation of geological and geomorphic features was conducted, followed by collection of surface sediments from river channels. Laboratory analyses included granulometry, textural statistical parameters, and heavy mineral analysis of 53 sediment samples collected from the entire reach of the Vaigai River from upstream to downstream, the majority of them were coarse sand, moderately sorted, finely skewed and platykurtic. Barring a few aberrations, a gradual increase in roundness of the grains from the headwaters to the basin outlet is recorded in the present study. The transportation of sediments is characterized by suspension with rolling. Discriminant plots of environmental and energy conditions affiliate the studied sediments to the riverine environment and unidirectional flow except few. Recycling of valley-fill sediments and negligible-noticeable sorting, weak transport characteristics during normal flow and effective exhumation-erosion-deposition during significant flow conditions were interpreted. Among the heavy minerals, the ubiquitous occurrence of hornblende followed by garnet, magnetite, epidote, rutile, zircon, and monazite in the decreasing proportion is documented. Elemental abundances in the heavy minerals of samples from the upper part of the basin show no significant/noticeable enrichment/depletion characteristics, whereas the samples of the lower part of the basin show uniformly abundant Si. These data and interpretations suggests that the channel bed sediments are mostly reworked and recycled, probably influenced by the river's flow on an antecedent valley and valley-fill. Within this general nature, aberrations are introduced by land use and other anthropogenic factors-imposed changes in sediment size, shape, sorting and heavy mineral occurrence and relative proportions.

Key words. *Climate, Environment, Fluvial dynamics, Stream bed sediments, Textural properties.*

Апстракт. Површински седименти речних корита пружају индиректне податке за разумевање како савремених, тако и палеоуслова седиментационих средина, климе, порекла седимената итд. У раду је спроведено

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систематско теренско картирање и одредба геолошких и геоморфолошкихих карактеристика, након чега су прикупљени површински седименти из речних корита. Лабораторијске анализе обухватале су гранулометрију, текстурне статистичке параметре и анализу тешких минерала на 53 узорка седимента прикупљена са целокупног тока реке Vaigai, од извора до ушћа. Већина узорака представљена је грубим песком који је умерено сортиран, зрна благо искривљена и платикуртична. Осим неколико одступања, у овом истраживању је забележен постепени пораст заобљености зрна од изворишта ка ушћу. Транспорт седимената карактерише суспендовање са котрљањем. Дискриминантни графици услова животне средине и енергије тока повезују проучаване седименте са речним окружењем и једносмерним током, осим у неколико случајева. Интерпретирани су процеси редепоновања седимената из попуњених долина, занемарљиво-приметно сортирање, слаба транспортна својства током нормалног тока, као и ефикасна ексумација-ерозија-депозиција током високог водостаја. Међу тешким минералима, забележена је свеприсутна појава хорнбленде, праћена гранатом, магнетитом, епидотом, рутилом, цирконом и монацитом у опадајућем уделу. Већа концентрација тешкх минерала у узорцима из горњег дела слива не показује значајне/приметне карактеристике обогаћивања/испражњавања, док узорци из доњег дела слива показују уједначену заступљеност Si. Ови подаци и интерпретације сугеришу да су седименти корита углавном поново обрађени и редепоновани, вероватно плављењем долине и акумулацијом материјала. Одступања су у вези са употребом земљишта и другим антропогеним факторима који утичу на промене у величини, облику, сортирању седимената и појавама тешких минерала и њиховим релативним уделима.

Кључне речи.
Клима, животна средина, динамика речног тока, седименти корита, текстурне карактеристике

Introduction

Rivers transport water fertile soil, and nutrients derived from their catchment areas and distribute them in the lower reaches, which serve as the foundation for agriculture, communities, and industrial activities. Despite being one of nature's most critical life-supporting systems, humans have been exploiting river systems for decades, with little understanding of how the river ecosystem operates and maintains its vitality (Naiman & Bilby, 1998). Rivers subjected to sand harvesting at rates exceeding natural replenishment often undergo channel degradation. This degradation leads to the incision of the entire river system including its tributaries (Ashraf et al., 2011; Mahmud et al., 2022). In addition, the environmental and geomorphic effects are not understood because of lack of the necessary data and insightful observations (Macfarlane & Mitchell, 2003; Kale, 2005; Ashraf et al., 2011; De Leeuw et al., 2010; East & Sankey,2020; Brierley et al., 2021). The fluvial system, water and sediments function as a coherent system are linked by a delicate environmental balance (Ramkumar, 2003).

Fluvial sediments are typically comprised of minerals that result from the weathering and erosion of parent rocks, textural and mineralogical compositions of the sediments are strongly influenced by provenance, tectonics, weathering, transport, and environmental conditions of depositional sites (Ramkumar, 2001; Ramkumar et al., 2000; Ramkumar & Sugantha, 2013; Ramkumar et al., 2015). Terrigenous sedimentary deposits contain a diverse array of heavy minerals, many of which initially crystallized under the conditions of temperature and pressure, quite distinct from those found on the Earth's surface. Within the sedimentary setting, these detrital minerals are subjected to weathering, with the most pronounced effects occurring in warm and humid climates, where chemical reactions tend to proceed more rapidly (White & Blum,1995; Brantley, 2003; Andò et al., 2012). The inferences drawn from granulometric characteristics, especially on the tectonic setting, provenance, climatic signals, etc., are further evaluated and or affirmed by the heavy mineral data. Heavy minerals are distinct in relation to specific major source terrains and their occurrence, assemblage, and textural characteristics are shaped by tectonic, climatic, and other environmental factors. Furthermore, scanning electron microscope (SEM) analyses of detrital grains (especially quartz) can reveal peculiar morphologies that may be associated with specific sedimentary processes or provenance (Cardona et al., 2005; Krinsley & Donahue,1968; Mahaney, 2002; Itamiya et al., 2019), thus helping to discriminate among different depositional environments (Damiani et al., 2006). In a prior investigation by Von Eynatten et al. (2012), conducted in a climatically distinct environment characterised by minimal chemical weathering, sediment composition is primarily governed by mechanical comminution across various grain-size categories. Raff et al. (2023) examined the accuracy of future sediment-delivery predictions by contrasting them with historical responses of the Ganges–Brahmaputra sediment load to climate change and monsoon strength during the Holocene.

Many researchers routinely analysed heavy mineral distributions to understand the provenance and processes that led to the formation of sedimentary deposits (e.g., Morton, 1985; Lihou et al., 1996; Cookenboo, 1997; Vital et al., 1999; Garzanti & Anto, 2007; Joshua & Oyebanjo, 2010; Bassis et al., 2016; Sun et al., 2022; Hisada et al., 2002; Morton, 1994; Sevastjanova et al., 2012). Hossain et al. (2021) undertook research to analyse the distributional patterns, micro-morphological characteristics of heavy mineral analysis, and the grain size parameters in order to ascertain depositional environment of the sand deposits in Jamuna River. Dixit et al. (2023) investigated intra-seasonal variations in chemical and mineralogical composition of sediments, aiming to constrain provenance. Similarly, Rahman et al. (2016) conducted studies on valuable heavy minerals extracted from the Brahmaputra River sands in Northern Bangladesh. Their study delved into the heavy mineral occurrence and abundance in the Brahmaputra River channel bed sediments and analysed their affinity with textural parameters, energy conditions of depositional, etc.

The Vaigai River located in the southern part of India, runs on an antecedent valley-fill of its own basin and has been a habitation site for human populations of microlithic-Recent times (Ramkumar et al., 2021, 2022a). Although the unique morphological characteristics of the basin have been subject of specific studies (Prabu & Baskaran, 2013; Ramkumar et al., 2019), various aspects of the basin have also been investigated. These include the identification of potential groundwater recharge zones (Kaliraj et al., 2015), the physicochemical parameters of surface water in theVaigai River near Madurai city were examined by (Mathuram, 2017; Balaji & Thirumaran, 2019), the grain size distribution of few selected locations along the river channel (Arun et al., 2019), flood events (Ramasamy et al., 2022; Nagalapalli et al., 2019) and radiation levels of sediments at few selected locations of the river channel (Ramasamy et al., 2014). As these data are crucial for understanding the tectono-climatic and environmental conditions of the river basin, this paper aims to document the granulometric and heavy mineral characteristics of the riverbed sediments to constrain on depositional environmental conditions, tectonics, climate, provenance, and anthropogenic influences, as well as to create an environmental baseline data.

Regional setting and the study area

The Vaigai River Basin (VRB, Fig.1) is located between 9°15’ to 10°20’N Latitudes and 77°10’ to 79°15’E Longitudes and covers parts of the Theni, Dindigul, Madurai, Sivagangai, and Ramanathapuram districts. The river originates at the Periya Pothigai hills of Western Ghats at an elevation of about 1200 m and traverses for about 270 km. Flowing northeast, the river traverses the Cumbam region, situated between the Palani Hills to the north and the Varushanadu Hills to the south. As it continues along the eastern corner of the Varushanadu Hills, the river takes a southeastward course and ultimately debauches into the Bay of Bengal at Palk strait in Ramanathapuram District (Chandran et al., 2016). Major tributaries of the river Vaigai include Upper Vaigai, Varahanadhi, Manjalar, Varattar-Nagalar, Marudhanadhi, Sirumalaiyar, Uppar and Satiar, originate in Palani hills and Sirumalai hills.These tributaries join the Vaigai along its course. Upper Vaigai River originates in the Alagar hills and joins Vaigai near Manamadurai.

This river basin evolved into its present configuration through five major landscape developmental stages. These include the inheritance of Mesozoic valley/structures during the Late Jurassic–Early Cretaceous period, drainage reversal, the initiation of Cenozoic–Recent river basin evolution, intense peneplanation during Miocene–Pliocene, intense incision during Pleistocene, periodic climatic extremes during Early Cenozoic, (Palaeocene–Eocene, Oligocene), accompanied by pedogenesis, terrace formation, and sedimentation (Ramkumar et al., 2019). Lithologically, the basin area (Fig. 1) is encompassing charnockite with metasedimentary rocks such as garnet-biotite-sillimanite gneiss, garnet–biotite gneiss, quartzites and calc-silicates constitute the southern part of the basin. The western part of the area exhibits distinctive geological features, with two different prominent groups of hornblende-biotite and orthopyroxene-biotite (charnockite) gneisses. One being quartz-rich and the other is feldspar-rich rock, and alkali granites. On the other hand, the eastern part consist of extensive charnockites and enderbites with heterogeneously dispersed quartzites and a series of calc-silicate rocks (Cenki & Kriegsman, 2005; Yellappa & Rao, 2008). Observation reveals the formation of Miocene–Pliocene Kankar/palaeosol, recycling of palaeosol and development of Holocene–Recent soil (Ramkumar et al., 2019). A major structural trend namely the tectonic line (e.g., Santosh et al., 2014; Ramkumar et al., 2016, 2017) traverses near Manamadurai and the deltahead of this river is located east of this line, similar to the east coast deltas of India. The basin experiences semihumid to semiarid climate, and receives an annual rainfall of 952 mm. A notable feature of this basin is that it experiences short-duration, and high-intensity rainfall like the Peninsular River basins (Ramkumar et al., 2019) and is also susceptible to flooding.

Geomorphologically, the western side of the VRB is characterized by structural hills and valley complexes, an older alluvial plain, and bajadas (Fig. 2). The central elevated terrain includes pediplain, moderately dissected hills, residual hills, valley fill, and pediments. The lower part includes Eastern coastal plain, which is comprised of an older deltaic plain, beach ridge-swale complex, tidal flats, and numerous tanks. Most of which are man-made since historic-archaeological times and are currently well connected by a canal network and in use.

Methods and materials

The study includes mapping and sampling the trunk and major tributaries of the Vaigai River from the point of origin to the point of confluence, covering a stretch of about 258 km. It is followed by collecting stream bed sediment samples from different locations in the Vaigai River trunk channel (Fig. 1). Data on field scale geology, structure, channel morphology and cross-section, landuse, vegetation, and soil characteristics were also collected from the field. These data were supplemented with thematic maps on geology, structure (source: Geological Survey of India Map), drainage (source: mapped from toposheets from SOI), rainfall (sources: IMD and www.indiawaterportal.org), are used for corroboration with the interpretations made on the granulometric and other data.

Textural analysis

Sediment samples were collected from the main channel or trunk channel. Locales of successive sampling varied between 3–12 km depending on sediment availability and accessibility. A total of 53 samples were collected and analysed for the present study. At each site, after collecting geographic coordinates through GPS, sediments were collected using a 10 cm × 20 cm PVC pipe, ensuring uniform sample size. Approximately 1 kg of sample was collected from each site, packed in an airtight PVC bag, labelled and transported to the laboratory. The sediments underwent laboratory analysis, and the computation of textural parameters was undertaken using the methodologies detailed in Ramkumar et al. (2000a) and Ramkumar (2001, 2007). In the laboratory, the samples were air dried, thoroughly

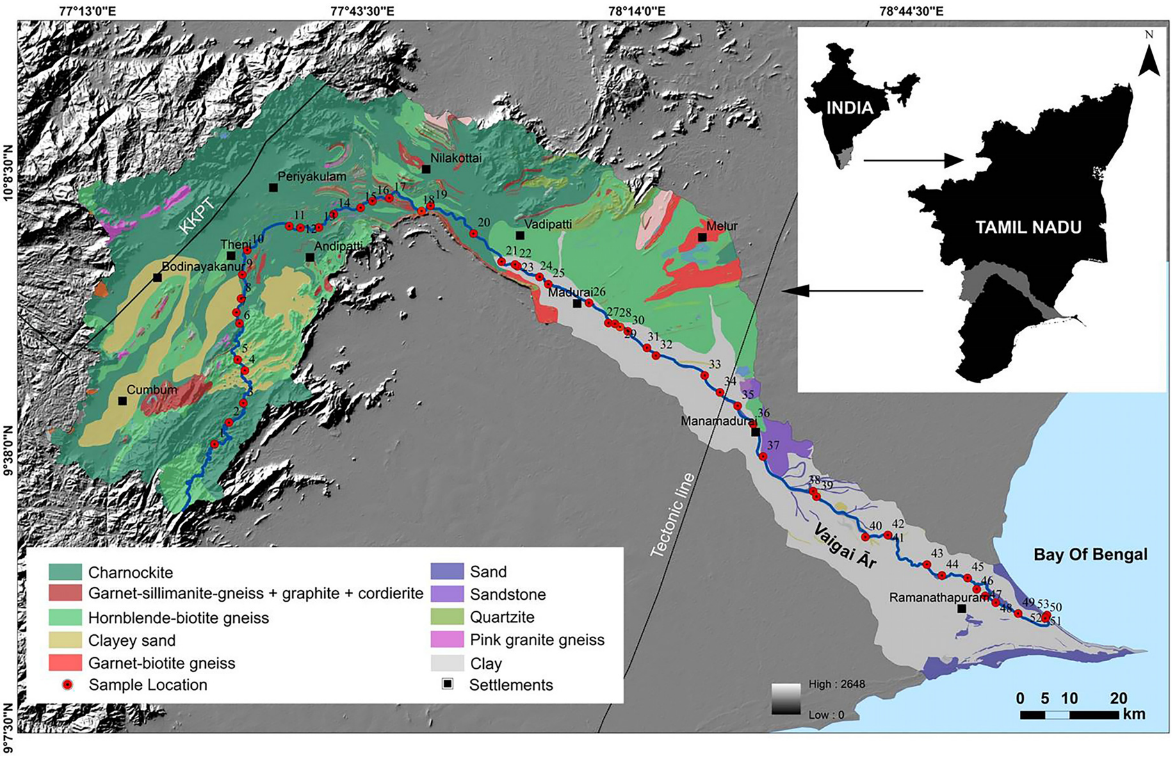


Fig. 1. *Location of the study area; showing the location of selected 53 sediment samples from catchment to confluence along with lithology.*

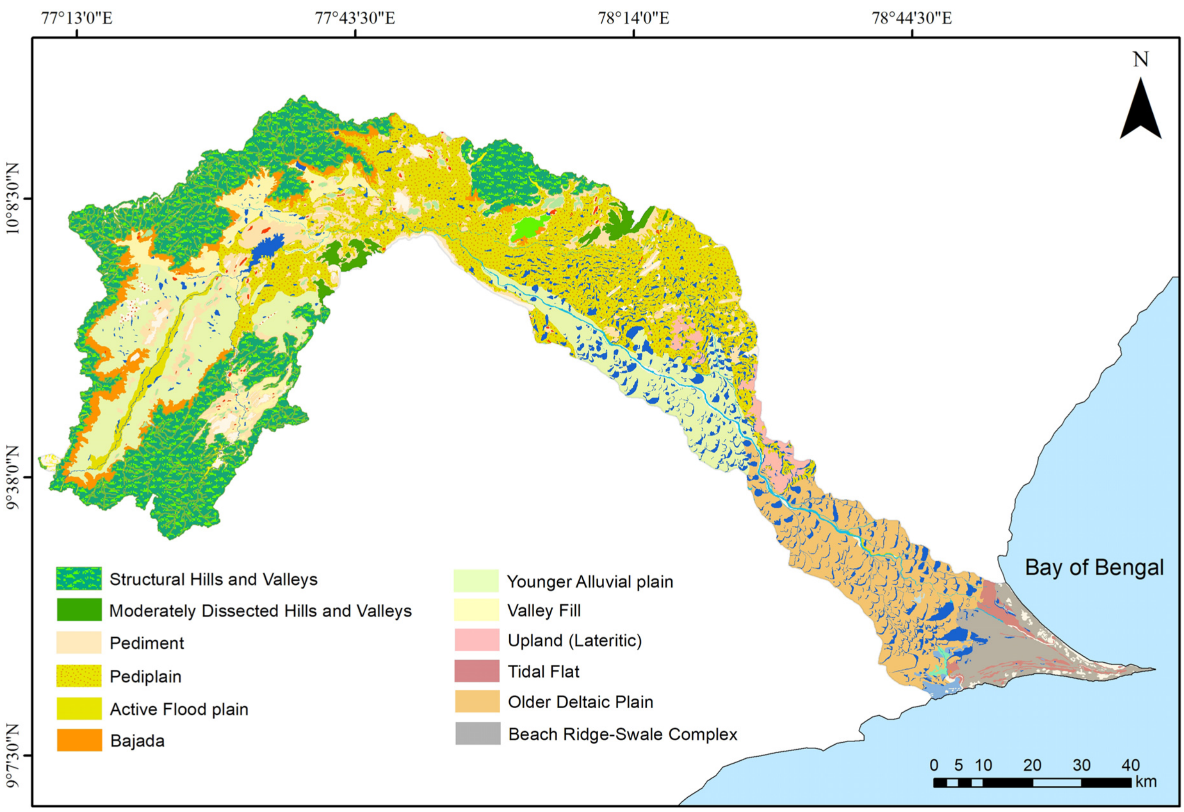


Fig. 2. *Geomorpology. Vaigai Basin is characterized by a western mountainous terrain with structural hills and valley complexes, an older alluvial plain, and bajadas. The central elevated terrain includes a pediplain, moderately dissected hills, residual hills, valley fill, and pediments. In the lower part of the basin lies the Eastern coastal plain, which is comprised of an older deltaic plain, beach ridge-swale complex, tidal flats, and numerous tanks.*

mixed, homogenized, cone and quartered to obtain approximately 50 gm of sediment subsample. Large shell fragments, organic material, or pebbles, if present, were removed. These subsamples were transferred to a pre-cleaned glass beaker. The samples were cleaned through three stages of treatments by hydrogenperoxide, 10% v/v HCl and quasi-distilled water. This process aims to remove organic matter, shell calcite and other contaminants from the samples. These subsamples were then dried in an air-oven overnight at 60° C and weighed and dry-sieved in an automated sieve-shaker with ASTM testsieve sets of ½ ϕ intervals (Ingram, 1970) for about 20min. The separated size classes of sediments were then weighed and tabulated. These data were converted into ¼ ϕ intervals with a computer algorithm (Ramkumar et al., 2000; Ramkumar, 2001, 2007), and then cumulative percent according to ϕ interval were calculated and plotted in a semi-log graph sheet for generating requisite data to computethe graphic mean (Mz), standard deviation (SD), skewness (SK) and kurtosis (KG). Furthermore, the input data required for several bivariate and other discriminant plots (discussed in the later section) were also obtained from the cumulative percent of the sediment samples.

Heavy mineral analysis

The method of Mange & Maurer (1992) was followed to separate and prepare the heavy mineral samples. Heavy minerals (density > 2.9) were extracted from the -1 ϕ to 4 ϕ (Coarse sand to fine sand) size fraction using tetrabromoethane ($Br_2CHCHBr_2$, density 2.89 gm/cc). Out of the total 53 samples analysed, only 38 of them contained both light and heavy mineral assemblages. The heavy minerals were then identified under a microscope (Leica DM2700P application suite version 4.13.0) and the percentage of particles of various minerals was calculated. In addition, heavy mineral separated from 6 samples, located at various regions of the river channel from source to confluence are chosen for examination under a Scanning Electron Microscope (Carl Zeiss EVO18 scanning electron microscope) fitted with energy dispersive spectrometer (EDS) for micromorphology and chemical mapping (SEM-EDS) of selected grains.

Results

Textural properties

On a basin scale, the studied samples are moderately sorted (0.87), finely skewed (0.24), platykurtic (0.84), and coarse sands (0.625). Within this general character, the grain size (Mz) varies from fine sand to pebble (–2.03 to 3), sorting (SD) varies from very well sorted (0.16) to extremely poorly sorted (4.38), skewness (SK) varies from strongly fine skewed (2.07) to strongly coarse skewed (–4.42) and the kurtosis (KG) varies from very Leptokurtic (2.39) to very platykurtic (–2.7).

Among the 53 sediment samples studied for granulometry, the majority of the samples fall within the coarse sand, few samples in the field of medium sand and only a four veering away from this range and falls in the field of fine sand, very coarse sand and pebble. Spatially also this character is observable in the absolute value curve of mean size (Fig. 3a) with little aberrations. The linear trendline ($R^2 = 0.0159$) also shows the monotony of grain size while the polynomial trendline ($R^2 = 0.1819$) shows an inflexion towards very coarse sand at the middle of the basin while the origin and confluence portions show the dominance of coarse-medium sand characters.

The standard deviation (SD) is the measure of scattered sediment grain sizes from the mean and is utilized traditionally to assess the sorting character of the sediments and indirectly the energy, nature of sediment source, influx and settling conditions. Most of the samples show a moderately well sorted nature with subordinate populations as moderately sorted and only a very few (<5) show a very well sorted nature and very poorly or extremely poorly sorted character. Similar to the mean size characteristics, the sorting of the sediments also shows monotonous nature from origin to confluence, as indicated by the linear trendline ($R^2 = 0.0025$; Fig. 3b) and the polynomial trendline ($R^2 = 0.0679$; Fig. 3b) which also shows an inflexion from moderately sorted to moderately well sorted nature at the middle of the basin and deflections toward poor sorting at the origin and confluence portions of the basin.

The skewness (SK) accounts the symmetry of the sediment size distribution with reference to the central tendency. A dominant proportion of the samples show a strongly fine skewed nature and a few within the range of nearly symmetrical at the confluence, except three samples indicating a strongly coarse skewed nature. Similar to the linear trendlines of mean size and standard deviation, the trendline of skewness also falls within a narrow range from origin to confluence ($R^2 = 0.0736$; Fig. 3c). Nevertheless, the deflection of the polynomial trendline ($R^2 = 0.1094$; Fig. 3c) does not mimic other granulometric parameters as it shows deflection towards coarse skewed nature near the confluence.

Kurtosis (KG) is the indicator of the sorting character of the grain size distribution concerning the endsizes of the grain size range. Quite akin to the other parameters, the occurrence of a narrow range of platykurtic to mesokurtic nature for most of the samples could be discerned from the absolute value curve of the kurtosis in Figure 3d. This curve is superimposed on the general trend, showing a clear linear change ($R^2 = 0.0753$) from leptokurtic (origin) to very platykurtic (confluence) nature (Fig. 3d). Additionally, an initial deflection from mesokurtic to leptokurtic is followed by relatively featureless domination of platykurtic nature through out the basin, culminates at deflection towards very platykurtic near the confluence. This trend is reflected in the polynomial trendline ($R^2 = 0.1146$; Fig. 3d).

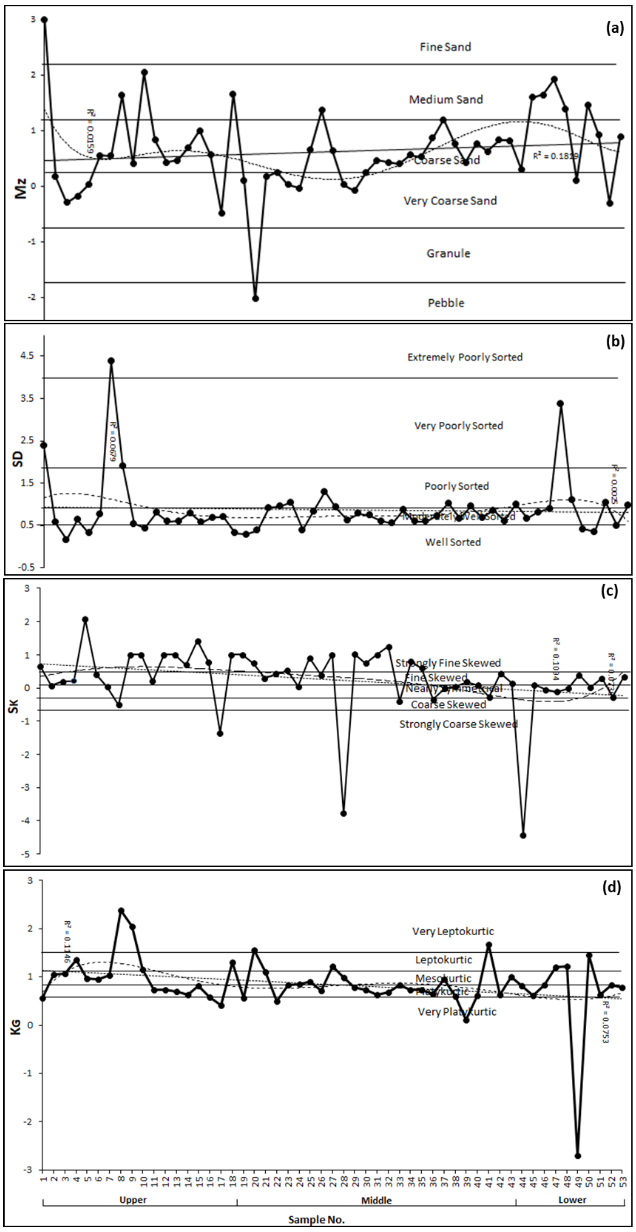
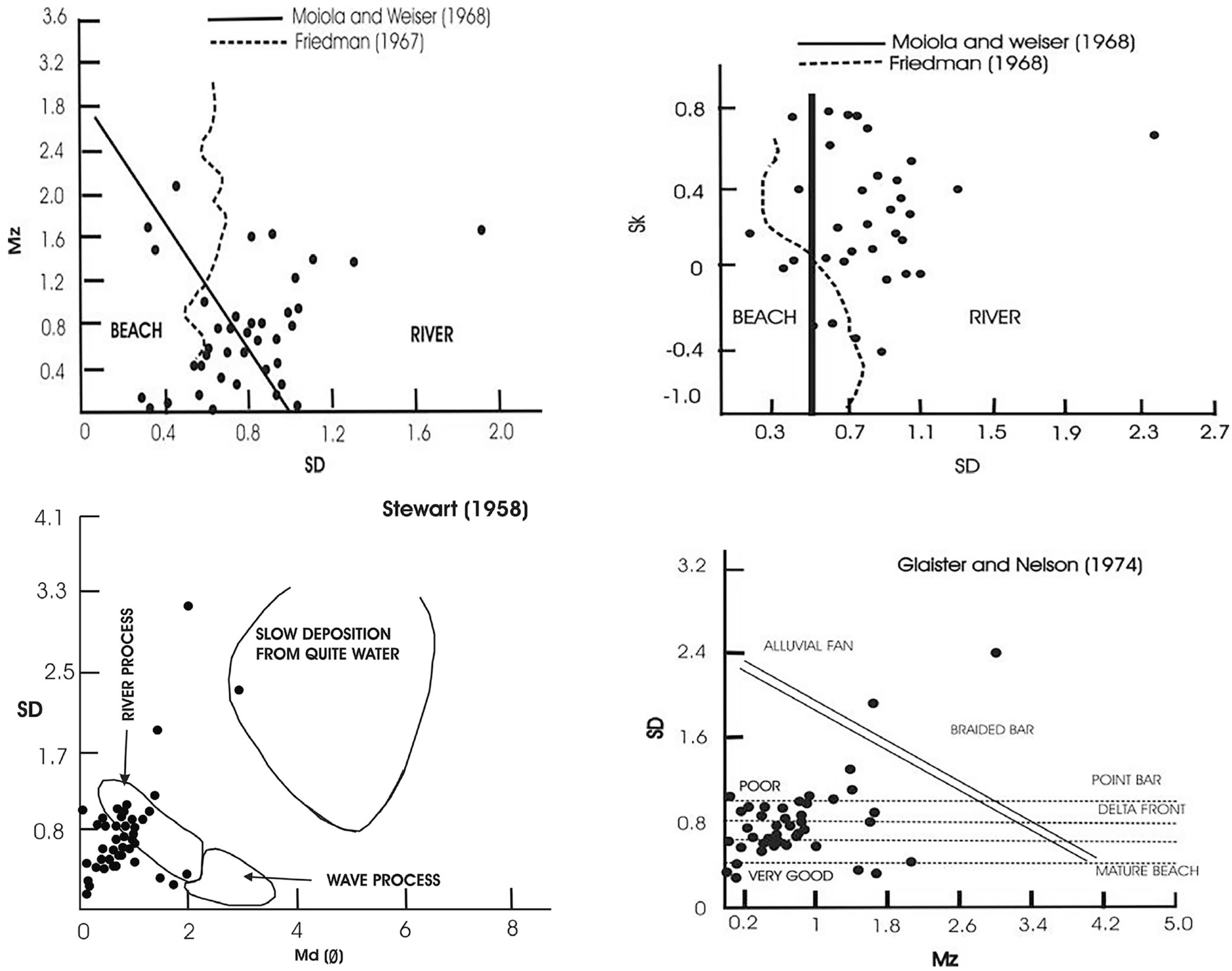


Fig. 3. *Downstream trends of the textural parameters of the Vaigai River.* ***a.*** *Absolute value curve of mean size;* ***b.*** *Sorting of most of the sediments shows moderately sorted;* ***c.*** *A dominant proportion of the samples show strongly fine skewed nature;* ***d.*** *Curve of Kurtosis varies from leptokurtic (origin) to very platykurtic.*

Environmental setting and processes

The discriminant lines proposed by Friedman (1967) and Moiola & Weiser (1968) were depicted in two distinct diagrams utilizing Mz and SD as variables, as illustrated in Figure 4A and SD and SK (Fig. 4b) to classify the dominant proportion of the samples in the river field, except for few in the MZ-SD (Fig. 4a) and very few in the SK-SD (Fig. 4b). Stewart's Discriminant diagram of standard deviation (SD) and Median (Md) values in ϕ scale for use in interpretation of dominant depositional process/energy conditions (Stewart, 1958) shows the majority of the samples falling in the river process field as a closely spaced cluster, with no samples fall near wave process (yet within the river field),



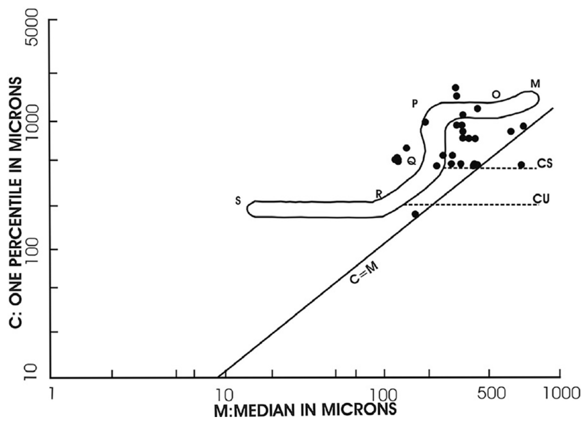


Fig. 4. *Discriminant diagrams of environments, energy, transport and depositional processes.* ***a.*** *Diagrams based on Mz and SD;* ***b.*** *SD and SK;* ***c.*** *Stewart's Discriminant diagram of standard deviation (SD) and Median (Md) showing most of the samples were deposited by river process except few samples;* ***d.*** *Plotting the Mz and SD data on a discriminant diagram after Glaister and Nelson (1974), show that most of the samples fall within the delta front and point bar and few are in the mature beach and two in the alluvial fan environment fields;* ***e.*** *The CM plot of transport mode/process exhibits all the samples above the maximum grain size transported by graded suspension.*

then, one sample in slow deposition from quite a water field and a few others far away from all the fields (Fig. 4c). Plotting the Mz and SD data on a discriminant diagram (Fig. 4d) after Glaister & Nelson (1974), shows that most of the samples fall within the delta front and point bar, a few are in the mature beach and two in the alluvial fan environment fields. The CM plot (Fig. 4e) of the transport mode/process exhibits all the samples above the maximum grain size transported by graded suspension. Within this field, transport the primarily occurred via suspension with rolling for most samples, while a fewer samples were transported through a combination of rolling and suspension.

Heavy mineral occurrence and distribution

Among the 53 samples processed for heavy mineral separation, only 38 samples contained heavy minerals. Individual grains were counted to investigate the mineral abundance, and subsequently, the percentage of the heavy minerals was computed (Fig. 5). The heavy minerals recognised are hornblende, zircon, magnetite, andalusite, biotite, tourmaline, kyanite, muscovite, augite, rutile, pale brown hypersthene, ilmenite, sphene, sillimanite, staurolite, epidote, limonite, monazite, and a variety of garnets including almandine, pyrope, spessartine, and grossular (as shown in Figs. 6 & 7). Hornblende content ranges from 23% to 74%, garnet from 10 % to 44.5 % and magnetite from 2.5% to 50%. The occurrence of other minerals is as follows: epidote (0.0% to 12.5%), staurolite (0.0% to 5%), rutile (0.0% to 2%), monazite (0.0% to 5%), ilmenite (0.0% to 2.5%), zircon (0.0% to 2.5%), mica (0.0% to 3%), limonite (0.0% to 1.5%), sillimanite (0.0% to 3%) and tourmaline (0.0% to 1%) (Table 1). Overall the heavy mineral population is higher in the upper Vaigai Basin and lowest in the lower Vaigai Basin. Most of the samples possess a higher proportion of hornblende followed by garnet and magnetite. Their proportions in each sample and variation from origin to confluence are shown in the Figure 8. The proportions of the heavy mineral occurrences in these samples vary from a minimum of 0.00% to a maximum of 44.26% and a mean value of 12.51. Spatially, higher abundance of heavy minerals occupied the middle part of the basin and lower proportions at the confluence are observed. On a linear trend, a gradual reduction ($R^2 = 0.0552$) from source to confluence (Fig. 5) is depicted by the distribution pattern of the heavy minerals. The occurrence of a higher proportion in the upper part of the basin (44.6%), lower near the catchment and lowest near the confluence are depicted by the polynomial trend line ($R^2 = 0.2548$). Morphologically, the heavy mineral grains exhibit a variety of shapes from angular to rounded. Data on relative proportions of angular, subangular, subrounded and rounded heavy mineral grains of individual samples are presented in Figs. 8a–d. From these figures, occurrences of ubiquitous, almost equal proportions of angular (Fig. 8a) and subangular (Fig. 8b) heavy mineral grains, domination of sub-rounded (Fig. 8c) grains in the upper part of the basin and domination of rounded (Fig. 8d) grains in the lower part of the basin are perceptible. The mean values of each of the morphological categories revealed a decreasing trend of subangular (37%) > angular (25%) > rounded (21%) > subrounded (18%). Within this general trend, sudden increases in relative proportions of angular and subangular grains in proximity to the confluences of tributaries, dam exit points, etc, and sudden changes in relative proportions of sub-rounded grains in the upper part of the basin and rounded grains in the lower part of the basin occur. Nevertheless, the number of samples that contain above average % of all these morphological grains are in the ranges of 16–17, uniformly.

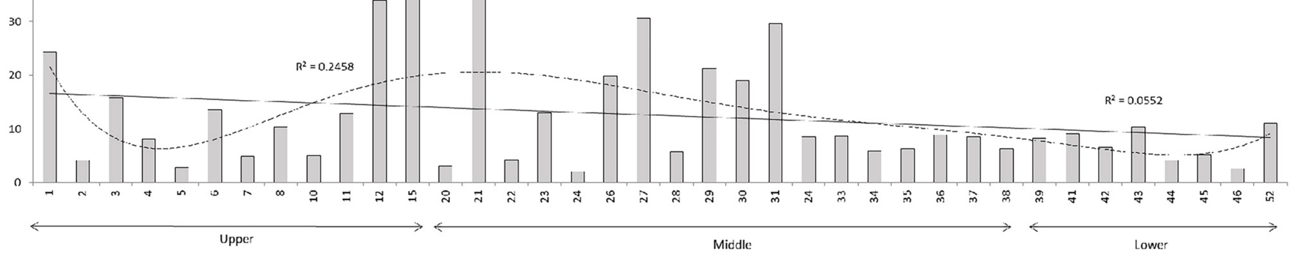


__Fig. 5.__ Occurrence of relative proportions of heavy mineral for selected 38 samples.

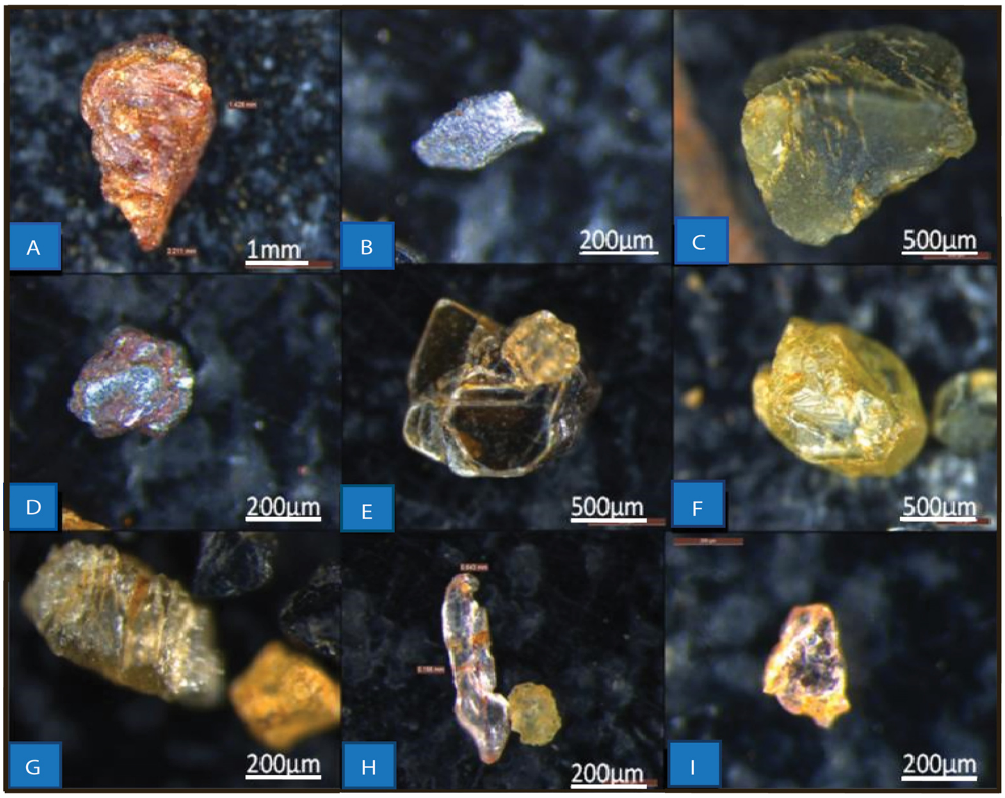


***Fig. 6**. Images of selected heavy mineral types A) Garnet Group of Hessonite B) Magnetite C) Hypersthene with inclusions D) Andalusite E) Biotite F) Sillimanite G) Zircon with cleavages H) Tourmaline I) Fractured Zircon*

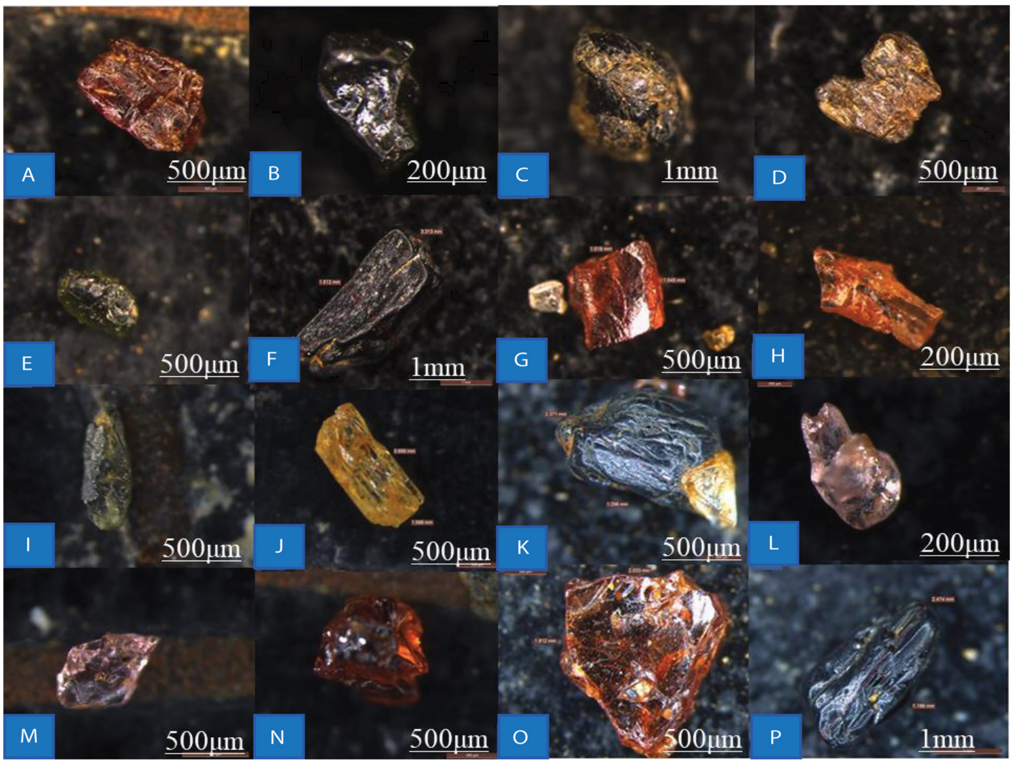


***Fig. 7.** A) Pyrope B) Ilmenite C) Ilmenite D) Hornblende E) Sphene F) Hypersthene G) Pyrope H) Hessonite I) Sphene J) Sillimanite K) Magnetite L) Andalusite M) Andalusite N) Rutile O) Almandine P) Hornblende*

***Table** 1. The recognised heavy minerals and their propotions in percentage.*

S. No	Hornblende	Garnet	Magnetite	Epidote	Rutile	Monazite	Illmanite	Zircon	Staurolite	Hypersthen	Tourmaline	Limonite	Sillimanite
1	34	39.5	25	1.5	0	0	0	0	0	0	0	0	0
2	33	44	16	3	0	0	0	0.5	0	2	0	1.5	0
3	23	15.5	48	7	0	0	0	1.5	5	0	0	0	0
4	39	35	21	0	0	0	0	0	2	3	0	0	0
5	37	20	38	5	0	0	0	0	0	0	0	0	0
6	40.5	32.5	27	0	0	0	0	0	0	0	0	0	0
7	44.5	28.5	17.5	3.5	1.5	2.5	0	0.5	0	1.5	0	0	0
8	42	19	28	4	0	0	0	0.5	4	1	0	1.5	0
9	33	35	24.5	2	1	0	0	0	4.5	0	0	0	0
10	37.5	22.5	38	0	0	0	0	0	0	0.5	0	1.5	0
11	35.5	35	25	1	1	1	0	0.5	0	0	1	0	0
12	40	23.5	33	0	0.5	1	2	0	0	0	0	0	0
13	48	16	29.5	5.5	0	0	0.5	0.5	0	0	0	0	0
14	50.5	10	32.5	0	0	2.5	0	0.5	4	0	0	0	0
15	37.5	24	25	8	1.5	0.5	0	2.5	1	0	0	0	0
16	52	31.5	15	1.5	0	0	0	0	0	0	0	0	0
17	47.5	10	25	2.5	0.5	5	2.5	0.5	1.5	1.5	1	1.5	1
18	64	30	5	1	0	0	0	0	0	0	0	0	0
19	31	20.5	43.5	0	0	3	1.5	0	0	0	0.5	0	0
20	49	24.5	24	2.5	0	0	0	0	0	0	0	0	0
21	48	22.5	26	1.5	0	0	0	1.5	0.5	0	0	0	0
22	33.5	23	35	1	2	0	0	2.5	1	1	0	0	1
23	56	20	22	1	1	0	0	0	0	0	0	0	0
24	25	44.5	10	12.5	1.5	2.5	0	1	3	0	0	0	0
25	34	18.5	45	0.5	0.5	0	0	1.5	0	0	0	0	0
26	53.5	20	25	1	0.5	0	0	0	0	0	0	0	0
27	52	28.5	7.5	2.5	0.5	4	1	1.5	2.5	0	0	0	0
28	42.5	32.5	24	1	0	0	0	0	0	0	0	0	0
29	29	26	38.5	0.5	0	2	0	1	0	0	0	0	3
30	25	29	40	2.5	0	0	0	0	3.5	0	0	0	0
31	74	20	2.5	1.5	0	2	0	0	0	0	0	0	0
32	33.5	15.5	50	0	0	0	0	0	1	0	0	0	0
33	44	35.5	19	1.5	0	0	0	0	0	0	0	0	0
34	30.5	19.5	43	4.5	0.5	1	0	0	1	0	0	0	0
35	36	42.5	20	1.5	0	0	0	0	0	0	0	0	0
36	30	25	38.5	1.5	0	2	0	0	0	1.5	1	0	0.5
37	37	34.5	28.5	0	0	0	0	0	0	0	0	0	0
38	32.5	25.5	35	4.5	0	0	0	0	2.5	0	0	0	0
Min	23	10	2.5	0	0	0	0	0	0	0	0	0	0
Max	74	44.5	50	12.5	2	5	2.5	2.5	5	3	1	1.5	3
Avg	40.3	26.2	27.6	2.2	0.3	0.7	0.1	0.4	0.9	0.3	0.09	0.15	0.14

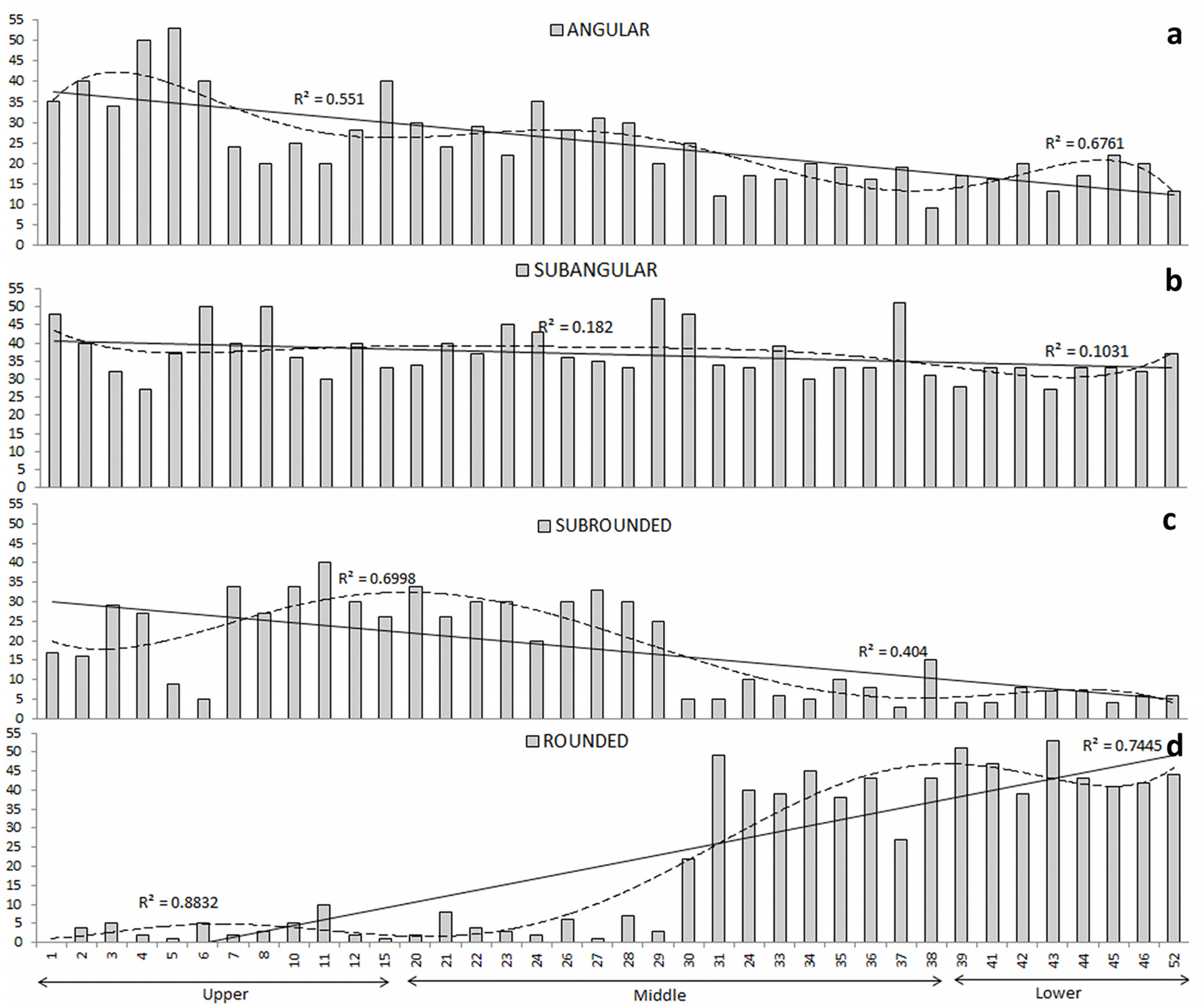


Fig. 8. *Percentage of morphological variations of selected heavy minerals such as **a**- angular, **b**- subangular, **c**- subrounded, **d**- rounded.*

Micromorphology and EDAX mapping

A total of 6 samples were examined under SEM and geochemically mapped by EDAX. The morphological variations observed under SEM are presented in Fig. 9. The element percentages in the Upper Vaigai Basin show variation in the following order: O > Si > Al > Fe > Ca > Mg, C > Si > O > Al > Mg > Ca >Fe, O > Si > Fe > Ti > Al > Mg >Ca > K. In the Lower Vaigai Basin, the element percentages follow this sequence: O > C >Si > Al> Mg > Ti , O >Si > Fe > Al > Mg >Ti>Ca> Na, C > Si > O > Al > Mg >Ca> Fe (Fig. 10).

Discussion

Downstream variations of depositional environmental conditions

The sediment grain size and textural parameters are commonly utilized for characterising the sedimentary environments (Inman, 1952; Tripathi & Hota, 2013; Sayem et al., 2021, 2023). The control of grain size distribution is influenced by various factors, including source composition, weathering, climate, and hydrodynamic alterations (Ramkumar et al., 2022a; Amalan et al., 2018; Gunasinghe et al., 2021;

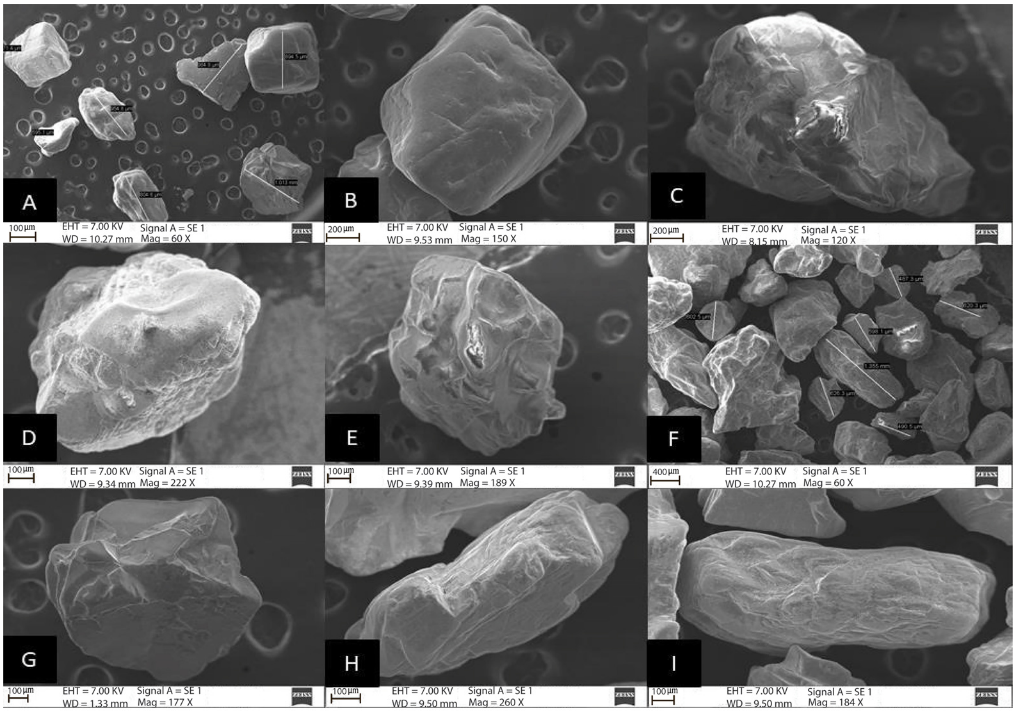


Fig. 9. *SEM images showing Sub-angular and Sub-rounded Grains B) Sub-rounded With Smoothened Edge C) Irregular Ridges D) Pitting E) Angular with Ridges F) Angular and Subangular Grains, G) Fractured Faces H) Elongated Ridges I) Elongated Grains.*

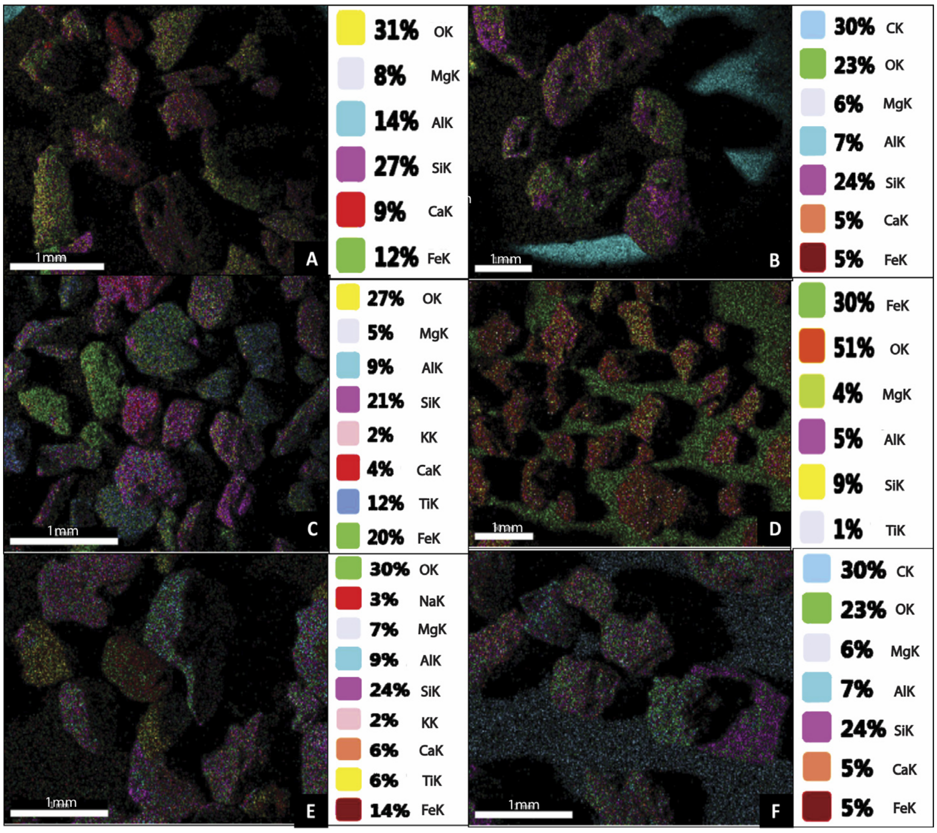


Fig. 10. *EDAX mapping of the elements and their percentages of selected heavy minerals showing variations in the Upper Vaigai Basin (A, B, C) and Lower Vaigai Basin (D, E, F)*

Perera et al., 2023). Friedman (1967) introduced graphic measurements specifically, the simple sorting measure, and the simple skewness measure, aiming to differentiate between beach, dune, and river sediments. Passega (1957, 1964) and Passega & Byramjee (1969) have endeavoured to establish the connection between textural characteristics and depositional processes, focusing on the relationships between specific sizes and the most probable depositional mechanism to classify clastic sediments by subdividing them into types indicative of their genesis (Ramkumar et al., 2000); discriminate one from the other (Ferrell et al., 1998; Ramkumar, 2001) or document the downstream variations (Ramkumar et al., 2015) and relate those variations with specific environmental parameters (Ramkumar & Sugantha, 2013) and geomorphic setting etc.

The studied sediment samples of the Vaigai River channel range from fine sand (3) to pebble (–2.03), with a standard deviation of 0.76. The Udden-Wentworth size class is classified based on an interval of 0.5 in the ϕ scale and a standard deviation of 0.76 represents a shift of more than one size class, which is considered abnormal, especially in a low-gradient, ephemeral river channel with reduced flow conditions. The graphic mean size of the sediments is influenced by multiple factors, including the source of sediment supply, the depositional environment, and the average kinetic energy of the agents responsible for sediment deposition (Khan et al., 2024). The Vaigai river runs on a antecedent valley, which is currently experiences resurgence from the catchment region (Juni et al., 2022). As a result of which newly exhumed sediments are exccesively supplied from the tributaries to the trunk channels- a quantity that could it be transported completely to the downstream region owing to the dwindling flow conitions (Dingle et al., 2016). These two observations signify the prevailing tectonic & presumed climatic control over the sediment transport-depositional condition within a river channel (Ramkumar et al., 2015). This inference gave further support by the occurrence of vast swasts of sand-sheet that covering the entire channel (Fig. 11), a phenomena also observed in other rivers in peninsular India (Ramkumar et al., 2015, 2025). The observed variation of more than one size class in a monotonous river channel suggests changes in environmental and energy conditions, which need to be identified (Ramkumar et al., 2015).

Unequivocally, all the samples collected from origin to confluence represent a riverine character in all the discriminant diagrams (Figs. 4a, b) with little/negligible variations. The absence of any estuarine and/or marine signatures in these sediments might imply a significant supply of sediments from the source that could not be reprocessed at a rate of supply to get estuarine and/or marine signature (Ramkumar et al., 2001) or additionally, recycling of alluvial sediments within the river basin by fresh, spatially varying zones of exhumation/erosion (Ramkumar et al., 2019). Notable exceptions are two or three samples that fall in the field of Alluvial fan (Fig. 4d) and these samples fall away in other environmental discrimination (Fig. 4b) and energy discrimination diagrams (Fig. 4c), reinforcing the interpretation of the fresh cycle of exhumation of the source area and supply of sediments.

The VRB has a unique hook–like morphology and the river runs on an antecedent valley (Ramkumar et al., 2019). Occurrences of topographically higher regions, mainly in the western and northwestern areas, and along with their association with freshly emerging cliffs, reactivated slides and alluvial fans, suggest an episodic supply of fresh sediments to the trunk river, which in turn runs on its own paleoalluvial valley-fill (Ramkumar et al., 2019). While occurrences of monotonous and/or almost indistinct proportional distributions of rounded, sub-rounded, sub-angular and angular grains may suggest ongoing mixing of freshly supplied sediments with that of recycled paleoalluvial valley-fill sediments in the trunk river, domination of sub-rounded grains in the upstream and rounded grains in the downstream clearly attest to the downstream differentiation of fluvial activity, which attempts, albeit unsuccessfully, to imprint its own fluvial textural maturity. The discriminant diagram of Glaister & Nelson (1974) testifies to this interpretation wherein all the samples fall within the delta field. However, a vaguely discernible trend of sediments that show progressive textural maturity from alluvial fan to mature beach (Fig. 4d) is observed.

Fig. 11. *Field Verification. A) sand deposits within the channel B) Thick sand deposits on the bank of the river channel C) meandering channel D) Location of thick sand hump as a result sand mining activity E) Vaigai Dam F) Thick sand deposits on the channel bank within the confluence of Vaigai river G) Near estuary of the river H) construction across the river channel I) Bedrock channel with pebbles and cobbles deposits.*

Examination of the modes of transport of the sediments with the help of the discriminant diagram (Fig. 4e) of Passega (1957), monopolytic confinement of all the samples except one above the C–S field (maximum grain size transported by graded suspension), and distribution of all except few within suspension with rolling and subordinate number of samples in rolling in suspension unequivocally, suggest supply of sediments from older sources (i.e., availability of older sediment layers, paleosols, thick weathering profiles in the source region), transport of the sediments from the source regions only during episodic, significant peak flows and transport of available sediment en masse. This inference concurs with the ongoing high-intensity; short-duration monsoonal flow conditions that characterise the VRB. The Vaigai River is a monsoon-fed one and prone to flooding since geological-historic times (Ramkumar et al., 2019, 2021, 2022a), and source regions of the sediments are episodically eroded during flooding and the sediment supplied to the rivers move as sand-sheets (Fig. 11). Downstream transport of these sediments is episodic, and each flooding event brings in fresh sediment and adds to the already deposited sediments within the channel. Thus, except the extreme catastrophic flood events, sediment transport in the Vaigai River system is punctuated, and the transport mode is rolling-suspension (Fig. 4e). It signifies the partial reworking of the sediments and prevalent punctuated/episodic transport mechanism/event.

Together, a weak transport-sorting capacity of the river system, which in turn functioned only during monsoon extremes, sourcing of fluvial sediments from its own paleoalluvial fill and minimal – noticeable quantities of fresh cycle of sediments from basin margin-alluvial fans, a feeble-distinct basin-scale distinction/differentiation of grain morphology as the characters of the Vaigai River system can be interpreted.

Minor variations in sample characteristics may be related to the changes in the riverbed characteristics which in turn may have been under the influences of changing climatic/landuse characteristics, anthropogenic interventions such as the construction of roads and buildings/bridges/dams etc (Malini & Rao, 2004; Pichuka & Roulo, 2024; Das et al., 2021). Study of sediment size and textural parameters serves the purpose of correlating the different sediment types and their respective deposition environments (Inman, 1952) and it aidsin distinguish between natural and anthropogenic processes operating within an environment. This characteristic is not unique to the river in question but can be observed in other comparable at their mature-stages (for example, the Godavari and the Krishna Rivers; Ramkumar 2001, 2007), quite oblivious to this simplified nature, the nuances and subtle differences as a result of myriad factors are as described herein.

The inclusive graphic standard deviation is a measure of the average dispersion of the distribution around the mean and is indicative of the level of sorting in sediments. The sorting ranges from extremely poorly sorted (4.38) to very well sorted (0.16), showing a significant variation. The sorting of sediment is moderately well sorted, with a standard deviation (0.71) higher than the minimum interval of 0.35, indicating a shift in the sorting class. However, there is a considerable variation in sorting characters, ranging from extremely poorly sorted to very well sorted, as indicated by the average. The observed moderately sorting nature could be ascribed to the incorporation of sediments featuring diverse grain sizes, possibly resulting from the reworking of beach ridges or via alluvial processes. This occurrence might be influenced by the consistent prevalence of strong wave convergence throughout the year (Gandhi, 2017). The skewness values also show a significant variation, ranging from strongly fine skewed to strongly coarse skewed, with a standard deviation of 1.03, suggests a shift of one skewness class interval. The graphic kurtosis (KG) indicates a departure from normality and a wide variation, ranging from very leptokurtic to very platykurtic. The grand average of KG is platykurtic, and the minimum value of kurtosis is very platykurtic, suggesting that certain forces other than normal depositional conditions may have influenced the observed sediment characteristics. The platykurtic characteristics observed in the sediment samples indicate the maturity of the sand, where the variations in sorting values result from the continuous addition of finer and coarser materials in different proportions. The changes in the sorting values are attributed to the ongoing influx of finer and coarser materials in varying proportions. Changes in the flow characteristics of the deposition medium can be deduced from variations in kurtosis values and specifically, exceptionally high or low kurtosis values indicate that a portion of the sediment has been sorted in different locations with a high-energy environment. Moreover, the kurtosis values provide insights into the maturity of sands by indicating the prevalence of rounded fine-grained particles with a platykurtic or mesokurtic nature (Baiyegunhi et al., 2017). The lower standard deviation values suggest well-sorted samples under low-energy depositional conditions (Lopez, 2017; Yun et al., 2023; Perera et al., 2023). The observed wide variation in the studied textural parameters is unexpected in a monsoon-fed fluvial system with reduced flow conditions in a low-gradient landscape, prompted an investigation into downstream variations. The analysis took into account linear and polynomial patterns in the context of natural trends and perturbations, particularly concerning the locations of anthropogenic intervention. The downstream pattern of Mz, as depicted by the linear trend (Fig. 3a) demonstrates a gradual transition from fine sand to pebble, as could be observed elsewhere in a fluvial environment. However, there are many aberrations, as indicated by the polynomial trend as well as the absolute value curve. Inclusive graphic skewness serves as a measure of the frequency distribution, providing insight into the position of the mean with respect to the median. Most important, it is geometrically independent of the sorting of the samples.

Toward downstream, the proportion of angular grains in heavy minerals in the overall sediments shows a decreasing trend (Fig. 8a) concomitant with an increase in the proportion of rounded grains (Fig. 8d). Along deltaic shorelines, heavy mineral concentration may decrease in the transport direction. This phenomenon is frequently observed in a situations where a reduction in sediment load in the accelerated erosion of deltaic cusps, consequent formation of placer lags, and lateral distribution of the selectively entrained heavy mineral-poor sediment fraction (Frihy & Komar, 1991; Li & Komar, 1992; Garzanti et al., 2002; Resentini et al., 2018). The rounding behaviour of various heavy minerals exhibits significant differences. The general consensus is that the roundness of grains is primarily attributed to the abrasion of grain margins, which occurs over extended periods due to transportation or reworking by the transporting medium (Russell, 1939). Nevertheless, the precise characteristics and duration of transportation and reworking necessary to generate rounded grains of different minerals remain inadequately comprehended (Zoleikhaei et al., 2016). In a recent study conducted by Garzanti et al. (2015), it was observed that minerals with metastable properties, such as pyroxene, amphibole, magnetite, ilmenite, epidote, and garnet, experience minimal rounding in fluvial and littoral environments. These studies have established that when compared to aeolian environments, the rounding of sand grains is relatively minimally influenced by the processes of fluvial transport and littoral reworking (Resentini et al., 2018).

The fluctuations in grain size population can be attributed to the influence of both natural and man-made obstacles, such as meanders, check dams and bridges, situated along the course of the river (Arun et al., 2019) and sand mining (Ramkumar et al., 2015). Lenzi & Comiti (2003) described the profile of a grain size distribution adjustment of trapped sediments in a mountain river (Italian Alps) stabilized by a sequence of boulder check dams. They reported that the drop height of check dams, the flow depth, and the step spacing of the dams affect scouring dynamics in a complex way. Their finding about the effect of check dams on grain size distribution adjustment of sediments confirmed the results previously obtained in laboratory tests. The grain size distribution of the sediments deposited behind the check dams depends on the type of sediments transported and the performance of the check dams in capturing the sediments. It is worth noting that sediment trapping by river dams can have adverse effects on the downstream channels and deltas (Hassalini & Nameghi, 2009). Sand mining results in significant environmental problems that are summarized by numerous researchers including, but not limited to, Bull & Scott (1974); Sandecki (1989); Kondolf & Swanson (1993); Kondolf(1997); Macfarlane & Mitchell (2003); Hemalatha et al. (2005); Shaji & Anilkuar (2014); Bhattacharya et al. (2019); Zou et al. (2019); Hackney et al. (2020); Rentier & Cammeraat (2022).

Provenance

Heavy mineral assemblages can be used for demarcating the probable sources from which they have been derived. The fluvial sediments originate from a range of parent rocks and undergo compositional changes due to multiple environmental processes. These processes include chemical weathering, selective physical breakdown, and hydrodynamic sorting during transportation and deposition. The analysis of river sediments in tracing studies can offer a distinctive signature of a region's geological characteristics and its geomorphological history (as demonstrated by Milliman & Syvitski, 1992; Heroy et al., 2003; Roddaz et al., 2005; Piper et al., 2006; Yang et al., 2009; Garzanti et al., 2007, 2010, 2015; James et al., 2023). The composition of heavy minerals in river sediment can undergo alterations due to a multitude of factors throughout the processes of formation, transportation, deposition, and subsequent changes such as lithological variations, hydrodynamic sorting, weathering, mechanical wear, and diagenesis (Morton & Hallsworth, 1999; Morton et al., 2005; Morton & Hallsworth, 2007; Krippner et al., 2015; Zhang et al., 2015). The minerals namely, hornblende, garnet, magnetite, epidote, rutile, monazite, ilmenite, zircon, staurolite, hypersthene, tourmaline, limonite, sillimanite, constitute the heavy mineral population of the studied samples. These mineral reflect the diverse lithology of the study area, which comprises charnockites, magmatic complexes, the peninsular gneissic complex, and khondalite rocks (Yellappa & Rao, 2008). Zircon, rutile, and hornblende, key indicators of provenance, display varying degrees of rounding, etching, and overgrowths, suggesting transport history and recycling processes (Gandhi, 2017). The rounded and sub-rounded grains of rutile suggest extensive transportation and or reworked nature, whereas the sub-angular grains of rutile indicate a probable origin from nearby sources, particularly khondalite and charnockites (Naidu et al., 2019). Hornblende, is indicative of metamorphic provenance, is associated with charnockite and retrograde charnockites (Mallik, 1987). The presence of hypersthene, garnet, chlorite, feldspar, and other heavy minerals further suggests derivation from peninsular gneiss, charnockites, migmatite, basic dykes, and schists (Santosh et al., 2017; Gao et al., 2021). Additionally, magnetite in river sands occurs as both liberated grains and complex intergrowths with silicate gangue minerals (Rahman et al., 2016). The southern part of the basin, dominated by Neoproterozoic charnockite and metasedimentary rocks such as Mg–Al granulites, garnet–biotite–sillimanite gneiss, quartzites, and cal-silicates, serves as a major source for these minerals.

Climate

The sediment supply from hill slope can exhibit significant spatial variations, which are attributed to different erosion processes or distinct lithology. These variations directly impact the bedload ratio and the size of particles transported within the river network, consequently influencing the equilibrium between sediment load and river carrying capacity. In recent years, numerous researchers have asserted that sediment flux, particularly the balance between bedload and carrying capacity, plays a crucial role in determining the rate and mode of fluvial incision into bedrock (Sklar & Dietrich, 1998, 2001; Howard, 1998; Hancock et al., 1998; Whipple & Tucker, 2002; Attal & Lavé, 2006; Scherler et al., 2017; Yanites, 2018; Sklar et al., 2020; Turowski, 2021).The sediment originating from bedrock on hill slopes undergo exposure to corrosive waters and temperature fluctuations, contribute to the reduction in particle sizes through processes such as mineral dissolution and fracturing. The annual mean rainfall of the VRB is about 952mm (Ramkumar et al., 2019). The flow of water and temperature variations on hill slope is influenced by climate conditions. Therefore, climatically driven differences in chemical and physical weathering might have played a role in regulating the reduction of sediment sizes during the journey from bedrock to the stream channel. Warm and wet conditions tend to accelerate chemical weathering, resulting in the delivery of relatively fine-grained sediments to the channel, as chemical processes tend to disaggregate rock at the scale of individual mineral grains. In contrast, landscapes featuring more resistant bedrock, colder climates, lower biomass, and faster uplift rates are prone toproviding coarser sediments to the channels.

CONCLUSIONS

– The channel bed sediments of the Vaigai River were sourced from their own antecedent valley fill and the transport-sorting capacity of the river system was weak and functioned effectively only during monsoon extremes. This has resulted, in a feeble-distinct basin-scale distinction/differentiation of grain morphology. Histotric-archaeological anthropogenic habitation and landuse change and changing climatic conditions may have contributed to these sediment characteristics.

– Prevalent tectono-climatic conditions, ongoing landuse changes and anthropogenic pressures/interventions into the natural fluvial system result in aberrations in the general downstream variations of textural parameters, heavy mineral distributions, etc. The heavy mineral signatures imply the provenance characteristics, recycling of older sediments and selective winnowing of prevailing transport characteristics mixing of fresh sediment influx into the stream channel sediments, perhaps as an indication of anthropogenic impact on the natural fluvial system.

– Though the heavy mineral compositions of the studied riverbed sediment samples show affinities with the lithologies that occur in the catchment, the lack of definitive and or significant, relationship, in association with the general increase in the roundness of heavy mineral grains could be construed as the result of sediment recycling, which in turn could be related with the dwindling influences of river flow-weak sediment transport mechanism, etc.

– The study has also documented the changing nature of fluvial system which is inhabitated from pre-historic times and is under anthropogenic and climate change pressuires which in turn result in its subdued/mixed expressions on sediment texture and heavy mineral distribution.

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Резиме

Депозиционе средине, порекло и утицај климе на текстурне карактеристике и дистрибуцију тешких минерала у седиментима речног корита реке Vaigai, југозападна Индија

Слив реке Vaigai налази се између 9°15’ и 10°20’ северне географске ширине и 77°10’ и 79°15’ источне географске дужине, и покрива делове округа Theni, Dindigul, Madurai, Sivagangai и Ramanathapuram. Река извире на планини Periya Pothigai у западном Гатима на надморској висини од око 1200 m и тече на дужини од око 270 km. Литолошки, подручје слива обухвата гранат-биотит-силиманитске гнајсеве, гранат-биотитске гнајсеве, кварците и калк-силикатне стене, које чине јужни део слива. Западни део подручја показује карактеристичне геолошке особености, са две различите, истакнуте групе гнајсева: хорнбленда-биотитске и ортопироксен-биотитске гнајсеве, при чему је први богат са кварцом, а други фелдспатом. С друге стране, источни део слива се састоји од гнајсева са хетерогено распоређеним кварцом и серијом калк-силикатних стена.

Седименти речног корита реке Vaigai воде порекло из речне долине, а капацитет система за транспорт и сортирање био је слаб и функционисао је ефикасно само током монсунских екстремених услова. Ово је довело до слабе и јасно уочљиве разлике у морфологији зрна на нивоу слива. Историјско-археолошко антропогено насељавање, промена употребе земљишта и променљиви климатски услови могли су допринети овим карактеристикама седимената. Тектонски и климатски услови, тренутне промене у употреби земљишта и антропогени утицај на речни систем доводе до одступања у текстурним параметрима, расподели тешких минерала итд. Присуство тешких минерала указује на антропогени утицај на природни речни систем, порекло материјала, редепозицију старијих седимената и прилив материјала у седименте речног корита. Међу 53 узорка који су обрађени за сепарацију тешких

минерала, само 38 узорака је садржало тешке минерале. Појединачна зрна су бројана како би се истражила заступљеност минерала, а затим је израчунат проценат тешких минерала. Препознати тешки минерали су хорнбленда, циркон, магнетит, андалузит, биотит, турмалин, кијанит, мусковит, аугит, рутил, бледо смеђи хиперстен, илменит, сфен, силиманит, ставролит, епидот, лимонит, монацит и различите врсте граната, укључујући алмандин, пироп, спесартин и гросулар. Иако састав тешких минерала из узорака седимената речног корита показује сличности са литолошким саставом слива, недостатак дефинитивне и/или значајне повезаности, у комбинацији са општим порастом заобљености зрна тешких минерала, може се тумачити као резултат редепозиције седимената, што би заузврат могло бити повезано са смањеним утицајем тока реке – слабим механизмом транспорта седимената итд. Истраживање је такође документовало променљиву природу речног система који је насељен још од праисторијских времена и који је под утицајем антропогених фактора и климатских промена, што је заузврат резултирало његовим различитим текстурним карактеристикама и расподелом тешких минерала.

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