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Research Article

Geochemical Characterization of Rasulpur - Subarnarekha River Mouths Estuarine Complex, EC of India: Provenance, Palaeo Weathering and Depositional Environment

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Abstract

Major and trace element geochemistry of sediments is a very useful tool for understanding the provenance, intensity of weathering, tectonic settings, and depositional environment of the sediments. Sediments collected from different geomorphic domains (onshore and nearshore) of Rasulpur to Subarnarekha River mouths estuarine complex, East coast of India, were analyzed for their geochemical (major, trace contents) and mineralogical characteristics to determine their provenance, compositional maturity, paleo-weathering condition, and depositional environment. From geochemical studies, it is evident that the samples from the nearshore area suffered more weathering than the onshore samples. Geochemistry of the sediments suggests the protolith of the area to be of intermediate to felsic source rocks. A relative increase in the Al_2O_3/TiO_2 ratio in sediments also suggests that they are derived mainly from intermediate to felsic source rocks. A strong positive correlation between Fe_2O_3, MnO, K_2O, MgO, CaO, P_2O_5, and major oxides with respect to Al_2O_3 indicates that they are associated with micaceous/clay minerals. The Index of Compositional Variability (ICV) indicating low compositional and mineralogical maturity of the sediments. The Chemical Index of Alteration (CIA) value clearly pointing towards intense to intermediate weathering in the source area sediments. Similarly, Chemical Index of Weathering (CIW) results also supporting the same trend of weathering. The results of Plagioclase Index of Alteration (PIA) suggesting moderate destruction of feldspars during source weathering, transport, sedimentation, and diagenesis. The Ternary plot of A-CN-K and the binary plot of CIA/ICV also suggest that both geomorphological domains are immature in nature and suffered intense to moderate weathering. Trace-element concentrations in sediments result from the competing influence of provenance, weathering, diagenesis, and sediment sorting. The felsic province is also corroborated by elevated values of Ba, K, and Sr. EPMA analysis reveals the presence of heavy minerals comprising Ilmenite, garnet as major constituents followed by sphene and rutile. Other minerals include sphene, epidote, amphibole, pyroxene, biotite, apatite, chlorite, tourmaline, muscovite, and alumino-silicate. The concentration of TiO_2 in Ilmenitedepicting a metamorphic signature with an igneous source. Micro-textural studies reveal different types of surface features of the grains, the various micro features have been produced by different transportational processes under different environmental conditions. Based on all geochemical and mineralogical data and different plots, it is evident that the sediments from both geomorphological domains are immature in nature and suffered intense to moderate weathering derived from mixed igneous and metamorphic sources.

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Keywords

Major Oxides, Trace Element, CIA, ICV, Rasulpur - Subarnarekha Complex

1. Introduction

The geochemistry of sediments is useful to determine the intensity of weathering, tectonic settings, depositional history and associated provenance of the sediments [2, 5, 8, 10, 15].

Due to the immobile nature of elements during the sedimentary process, major and trace element geochemistry provides more precise information on the study of provenance, tectonics, and paleoweathering than petrographic study [1, 8, 19]. Further, the trace element (i.e. Zr, Nb, Sc, Y, Cr) concentrations in the sediments are useful for discriminating provenance [14, 15, 40] due to their relatively low mobility during the sedimentary processes. Also, these elements are believed to be transferred quantitatively into detrital sediments during weathering and transportation; thus, their concentration can be useful in elucidating their parent rock characteristics [2-4, 6].

In the present study, an attempt has been made to identify the possible sources along with the weathering pattern of sediment samples collected from different geomorphic domains (onshore and nearshore) of the Rasulpur to Subarnarekha River mouth area. The samples have been studied in detail for comprehensive geochemistry.

Scanning Electron Microscopy (SEM) and EDX are also carried out to understand the micro-textures developed at different sedimentary stages by mineral grains, as well as for the characterization of depositional environments [11, 22, 24, 29]. SEM is a convenient and widespread technique for illustrating the morphologies of materials with a spatial resolution below 1 nm.

1.1. Study Area

The present study area covers parts of Midnapur and Balasore littoral tracts along the Kanthi coastal plain and Subarnarekha delta plain, occurring in West Bengal and Odisha states, respectively. The study area falls within Survey of India toposheetsnos [12]. 74 O/6, 10, 13, and 14 and is bounded in the northeast by the Rasulpur River (Midnapur) (87 ° 53' 9.6" E, 21 °47' 24" N, 87 °54' 3.6" E, 21 °46' 37.2" N) and in the southwest by the Subarnarekha River (Balasore) (87 °24' 3.6" E, 21 °34' 1.2" N, 87 °24' 39.6" E, 21 °32' 38.4" N) along a 65 km long coastal tract in the west. It is located in the East Medinipur District of West Bengal and Balasore District, Odisha (Figure 1).

Geologically, this is the coastal stretch of the Indo-Gangetic plain situated between the tectonically active Ganga Delta and the wave-dominated Subarnarekha Estuary. The area is drained by the Subarnarekha River flowing from north to south in the western part and the Hooghly River in the eastern part. It is mostly covered by Quaternary sediments and comprises recent alluvial deposits belonging to the Balasore-Contai coastal plain. The area exhibits smooth, nearly flat topography, gently sloping towards the sea. The lowest point noted in the district is around Bel (4.5m above MSL; 73 O/6), while the highest point noted is near Dhangikusum (338 m above MSL; 73 J/10). The oldest Quaternary deposits exposed in the area are of Pleistocene age, composed of fragments of quartz, phyllite, granite pebbles, and occasionally lateritized gravels. The Quaternary sediments in the area are mostly fluvial in origin and have been deposited by the Subarnarekha, Kasai, and Rupnarayan rivers.

The Sijua Formation constitutes the sediments of older alluvium, comprising hard clay and silt impregnated with caliche concretions. The overlying sediments of Basudevpur and Panskura formations constitute older flood regimes. Towards the sea, the underlying sediments become richer in arenaceous material, and on the beach area, clean dune sands of variable sizes are found to occur. The present-day floodplain deposits are composed of sand and silts of different layers. Geomorphic studies in the beach area have revealed that the process of beach formation is still in progress, and the shoreline is advancing, thereby exposing more and more land surfaces in the area. The area represents two distinct geomorphic provinces, namely (a) the upland area in the west and (b) the alluvial plains in the east. The district is not rich in minerals. Occurrences of fire clay (in Jarma), galena (in Gohalberia), mica (near Shiarbenda, Chakadoha, Dhenkia), ochre (in the northeast of Laobani), soapstone (in Khatkura and Kariaraha), and some gold dust from the Kasai River near Medinipur town are reported to be present. Estimated reserves of the deposits of the above-mentioned minerals are not known.

These surfaces primarily indicate fluvial sedimentary sequences during the Quaternary period (District Resource Map, Medinipur District). The Quaternary landscape of the Balasore area can be divided into several main geomorphic surfaces formed both due to erosional and aggradation processes. Bolgarh, the oldest geomorphic surface, is younger in age and forms a wide alluvial zone. This surface is also marked by a number of abandoned channels. Part of the fluvial facies of the Bankigarh Formation adjoining the Subarnarekha River is named the Subarnarekha surface/Formation, and its marine equivalent is termed the Basudevpur Formation. The Bankigarh surface is equated with a wide tidal flat, which at places is concealed under older longitudinal dunes with interdunal

depressions. On the other hand, the recent tidal flat with recent sand dunes and the beach is equivalent to the Present-Day surface of the fluvial regime. Quaternary sediments represent both fluviatile and marine facies. Balasore, being a coastal district covered by Quaternary sediments, has some problems of marine incursions and poor geotechnical properties of the basement soil (District Resource Map, Balasore district). The Panskura Formation is exposed in toposheets nos. 73 O/6 & 13, and the Bankigarh Formation is exposed in toposheets no. 73 O/6. The geological map of the toposheets numbered 73 O/5, 6, 9, 10, 13 & 14 is given in Figure 2. A generalized stratigraphy of the study area is provided in Table 1 as per Chattopadhyay& Mukherjee (1975). In the eastern part of the Digha sector, flattened remnants of older dunes are present. In Dadanpatrabar and Junput sectors, 'clay windows' are exposed during the monsoon. Steeply sloping irregular elongated dome-shaped sandy ridges of varying heights are present. Along the coastal belt from Digha to Dadanpatrabar, remnants of the older dune complex (semi-compact, feebly laminated, yellowish-brown sand), originally serving as beachfront dunes, are exposed and getting covered by the younger aeolian deposits from the beach face currently [13].

Table 1. *Stratigraphic succession of lithounit of the Purba-Medinipur Coastal Region, WestBengal.*

Lithology	Geological Unit	Age
Sands and silts in alternate layers	Present day flood plaindeposits.	Holocene
Fine to medium sands, greyish brown in colour	Present day beach deposits	Holocene
Sands, white to greyish yellow in colour, well sorted	Recent Sand dune Deposit	Holocene
Sands, silts and clays deposited in different flood regimes, no oxidation effect	Bankigarh Formation	Holocene
Sands with silts, clays, associated with Fenodulesand Clay	Panskura Formation	Holocene
Greenish grey clay, impregnated with calichenodules	Sijua Formation	Upper Pleistocene to Lower Holocene

The present day deposits include spit, active beach, berm, fluvial and aeolian deposits. It includes the landmass running parallel to the coastline and consists of very fine white to grey sands (beach sands) occasionally mixed with clay. Holocene sediments with parallel bedding are seen near Talsari area.

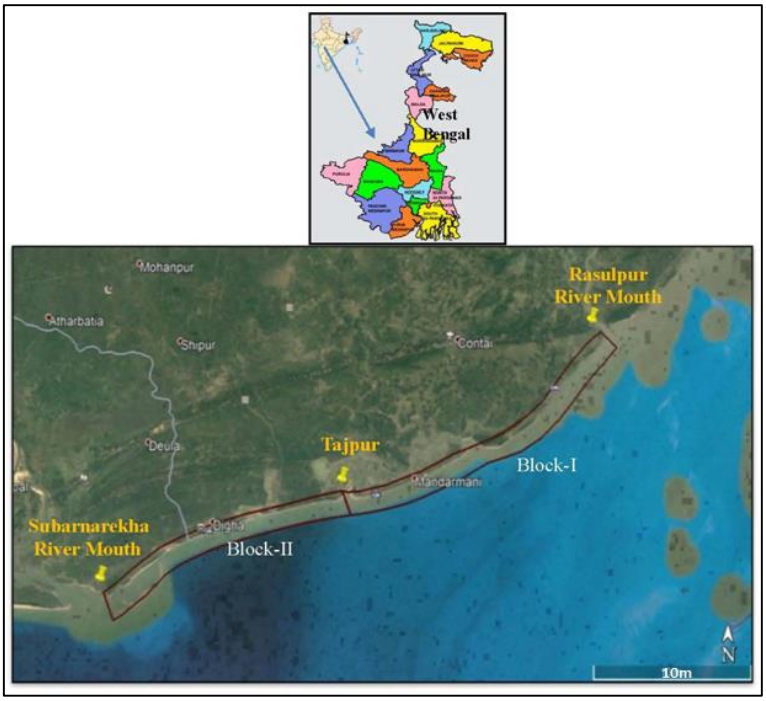

Figure 1. *Location map of Study Area Rasulpur river mouth to Subarnarekha River Mouth, East coast India.*

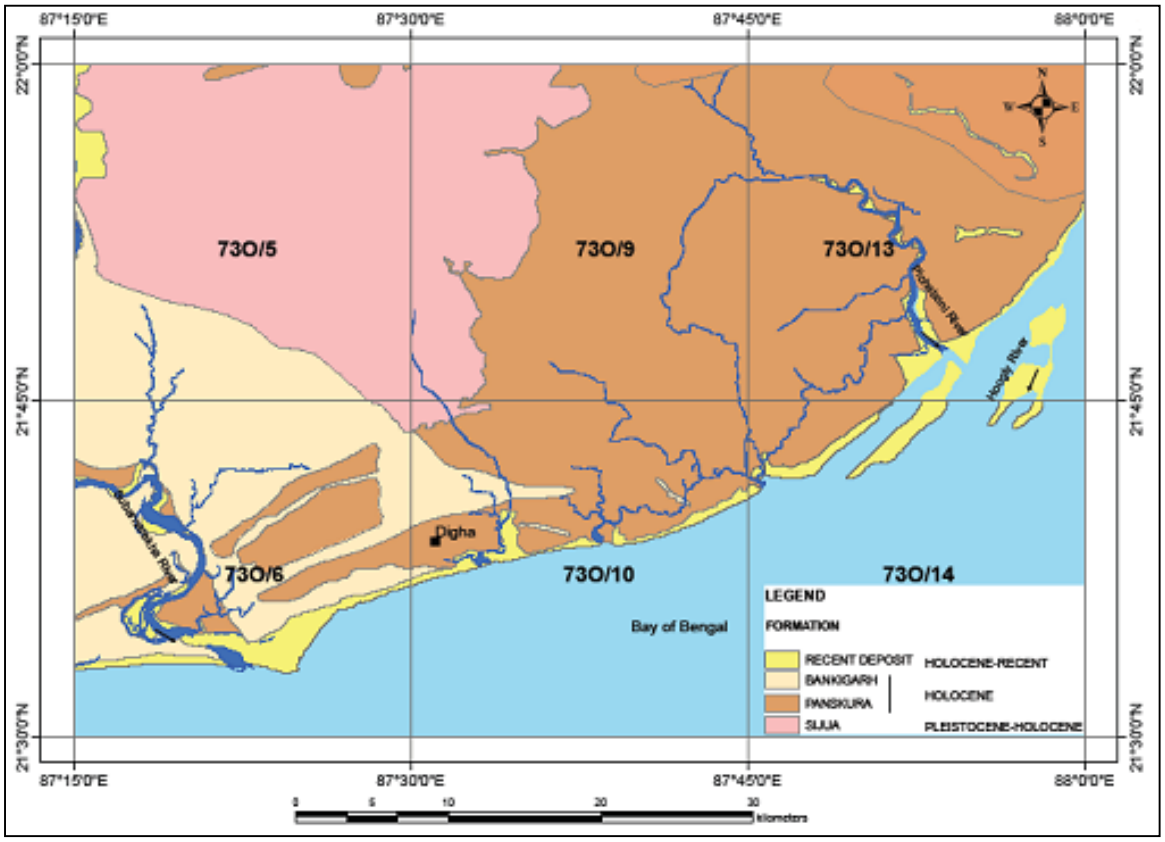

Figure 2. *Geological Map of the Study Area Rasulpur river mouth to Subarnarekha River Mouth, East coast India.*

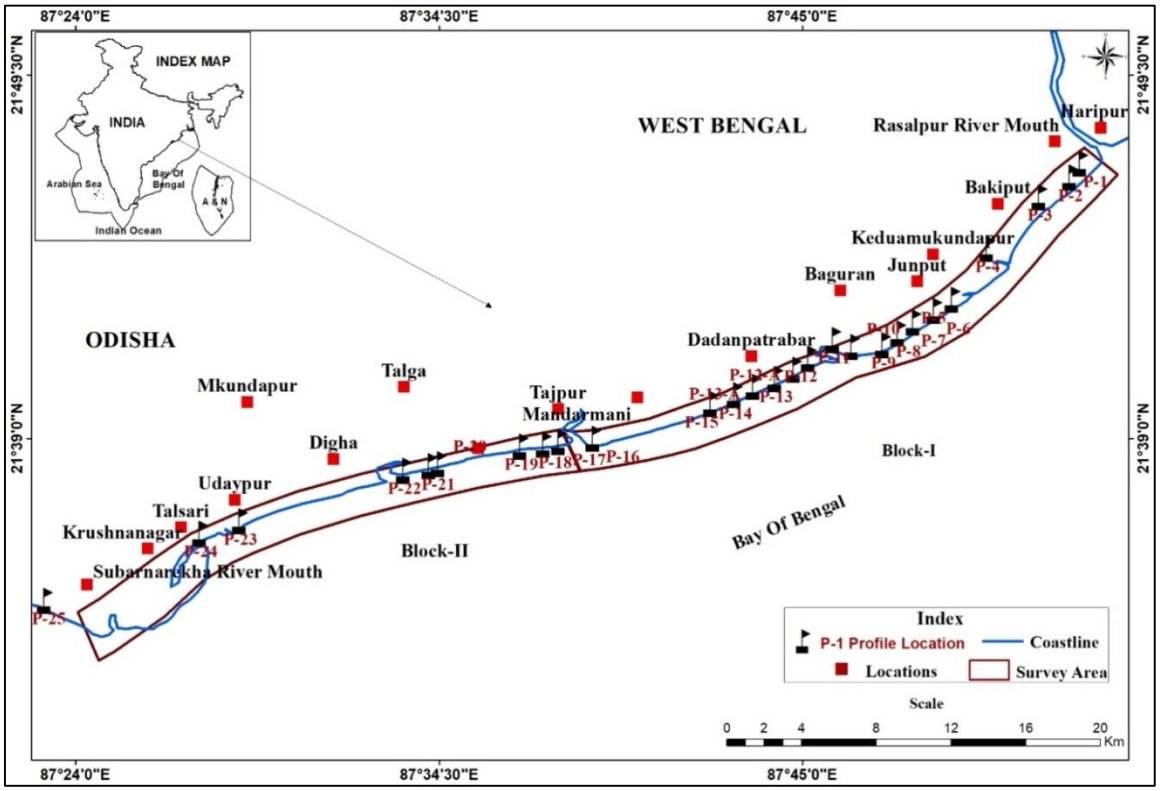

Figure 3. *Onshore sample location map of Study Area (Rasulpur river mouth to Subarnarekha River Mouth, East coast India.*

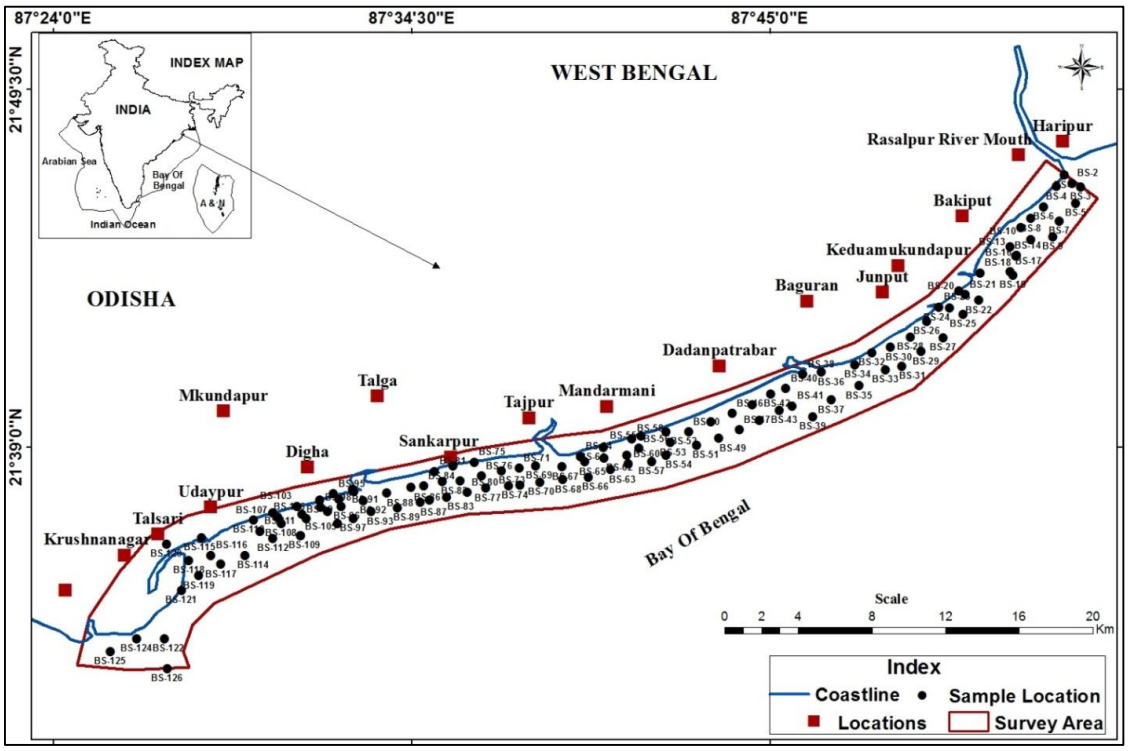

Figure 4. *Near shore sample location map of Study Area (Rasulpur river mouth to Subarnarekha River Mouth, East coast India.*

1.2. Methodology

Major oxides and trace elements were analyzed by XRF (X-ray fluorescence spectrometry technique) at the Chemical Laboratory, Kolkata, GSI, of the samples collected from different geomorphic domains of onshore and near shore (0-10 m isobaths) (tabulated in Table 2; Figures 3, 4). The samples were soaked in water for 24 hours to remove salt and then treated with 6% dilute H_2O_2 and dilute HCl to remove organic matter and carbonates. The pre-processed and homogenized samples were analyzed. Subsequently, the samples were dried in a hot air oven at 60 ℃. Furthermore, the samples (approximately 15g) were pulverized (homogenized) to minus 200 mesh size using a planetary ball mill (Retsch PM400) with an agate bowl and balls. The pulverized samples were then pressed into the form of pressed pellets with a diameter of 40mm in an aluminum cup over a bed of boric acid by applying a pressure of 20 tonnes using a Hydraulic press pelletizer (Insmart Systems). The prepared pellets were analyzed in a 2.4 kW WD sequential X-ray fluorescence spectrometer (PANalytical Magix-2424) equipped with PX1, PE 002, Ge 111, LiF 200, and LiF 220 diffracting crystals, as well as flow, scintillation, and duplex detectors. Samples were dried at 100 ℃ and heated at 900 ℃ to determine the percentage of loss on ignition (LOI) using standard procedures.

Onshore and nearshore samples representing all the geomorphic units have been selected for SEM & EDX study. Coarse, medium, and fine sand are chosen from each sample, and mono-crystalline quartz grains and heavy minerals are examined to study the morphological characteristics. The sand fractions were selected and treated chemically following standard procedures [20-22] to remove coatings of iron oxide and organic matter. The studies were carried out in the SEM Lab, Geological Survey of India, Central Headquarters, Kolkata. About fifteen to twenty grains were selected randomly from each sample for SEM & EDX study. Semi-quantitative energy-dispersive X-ray spectroscopy (EDX) analysis is performed, which is attached to the SEM. Analyses are conducted with an accelerating voltage of 15-20 kV and an electron beam current of 12 nA. Finally, the mounted grains were analyzed under a Scanning Electron Microscope, and photomicrographs were taken to study surface micro-texture to decipher the depositional environments, the mode of transport, and the diagenetic processes of coastal sediments based on the different microtextures on the grains.

2. Results and Discussion

2.1. Major Oxides and Trace Element Geochemistry

The major oxides concentrations of all the onshore and nearshore samples show the same trend. The analyzed samples are mostly rich in SiO_2 (67% to 87%; avg. 77% and 51.86% to 88.52% with an avg. 72.31%, respectively), followed by Al_2O_3 and Fe_2O_3 (12.40% to 5.74%, and 5.98% to 1.35%; avg. 9.08%, and 3.41%, respectively, and 17.84% to 5.17%, and

9.06% to 0.96%; avg. 11.32%, and 4.08%, respectively) (Tables 2, 3; Figure 5). The concentrations of K_2O, CaO, Na_2O, MgO, TiO_2, P_2O_5, and MnO are generally low compared to other elements (ranging from 3.60% to 1.76%, 3.30% to 0.95%, 1.95% to 1.14%, 2.82% to 0.21%, 0.40% to 0.05%, 0.14% to 0.01%, and 0.05% to 0.14%, respectively, with an average of 2.68%, 1.98%, 1.55%, 1.15%, 0.87%, 0.16%, and 0.07%, respectively, and 3.84% to 1.80%, 3.66% to 0.62%, 2.39% to 0.77%, 3.27% to 0.19%, 2.46% to 0.08%, 0.20% to 0.03%, and 0.0% to 0.14%, respectively, with an average of 2.85%, 1.61%, 1.39%, 1.56%, 0.93%, 0.09%, and 0.07%, respectively) (Tables 2, 3; Figure 6). The dominance of SiO_2 in the analyzed sediments is a result of the presence of free quartz derived from the felsic-dominated terrains. The total major oxide content is slightly higher in onshore sediments (98%) compared to nearshore sediments (96.20%). The major oxide composition in the **onshore** and nearshore samples shows a more or less similar trend, which is also nearly similar to the average concentrations of the PAAS (Post-Archaean Australian Shale) [43] (Figures 5, 6).

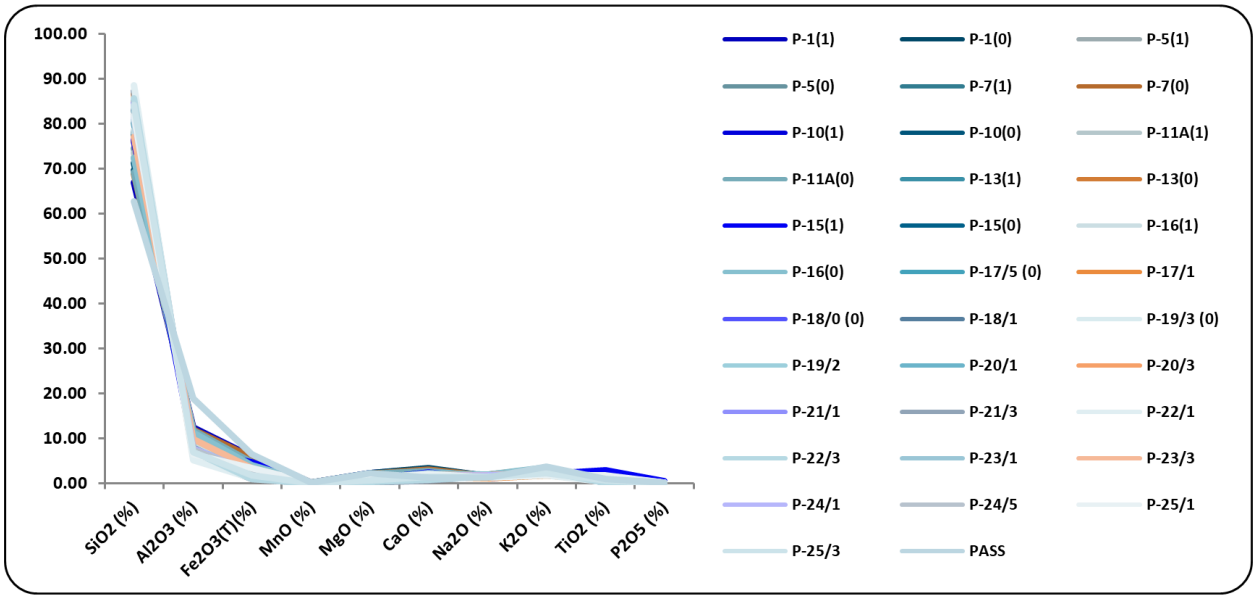

Figure 5. *Concentration of Major oxides of surface sediments samples for (1) Onshore and (2) Near shore sediment from Rasulpur to Subarnarekha River Mouth.*

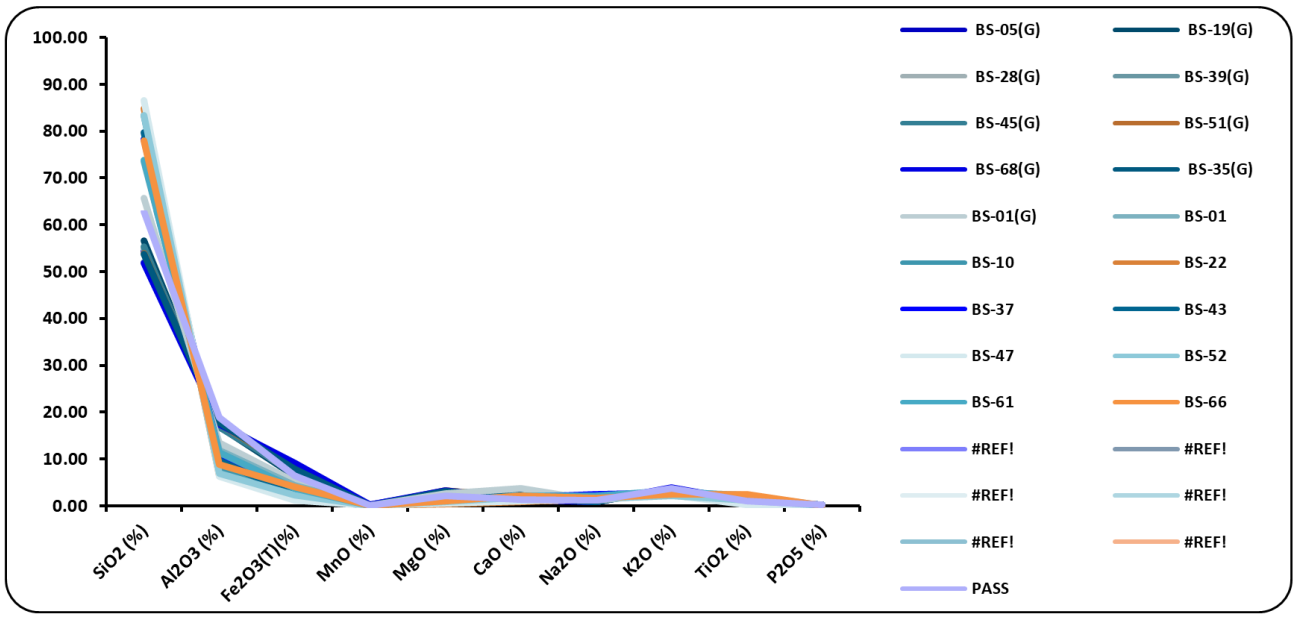

Figure 6. *Concentration of Major oxides of surface sediments samples for (1) Onshore and (2) Near shore sediment from Rasulpur to Subarnarekha River Mouth.*

The K_2O and Na_2O contents, and their higher ratios (K_2O/Na_2O avg. 1.73, 2.4; $K_2O/Na_2O > 1$), suggest that K-feldspar dominates over plagioclase (albite) feldspar. K_2O enrichment relates to the presence of illite as a common clay mineral in the samples, which is higher in nearshore samples (Tables 2, 3).

Table 2. *Major oxides concentration onshore samples from Rasulpur to Subarnarekha River Mouth (in wt %).*

Sl No	SampleNo	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (T)(%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	Total	Al_2O_3/TiO_2	K_2O/Na_2O
1	P-1(0)	69.64	11.49	4.27	0.10	2.23	3.30	1.61	2.59	0.82	0.19	96.24	14.012	1.609
2	P-1(1)	66.86	12.40	5.98	0.12	2.18	3.16	1.63	3.44	0.54	0.23	96.54	22.963	2.110
3	P-5(0)	74.53	8.90	3.86	0.09	1.44	2.95	1.24	2.21	1.14	0.18	96.54	7.807	1.782
4	P-5(1)	72.43	9.55	5.30	0.14	1.39	2.02	1.39	2.49	2.11	0.37	97.19	4.526	1.791
5	P-7(0)	68.80	11.85	5.71	0.11	2.03	3.05	1.58	3.13	1.26	0.20	97.72	9.405	1.981
6	P-7(1)	78.21	7.75	3.27	0.08	0.94	1.86	1.54	2.25	1.33	0.14	97.37	5.827	1.461
7	P-10(0)	71.21	10.72	4.65	0.09	1.57	2.56	1.66	3.09	1.29	0.17	97.01	8.310	1.861
8	P-10(1)	76.18	8.94	3.33	0.06	1.06	1.81	1.49	2.87	0.81	0.14	96.69	11.037	1.926
9	P-11A(0)	69.14	11.76	4.59	0.10	2.00	2.67	1.50	2.77	0.86	0.20	95.59	13.674	1.847
10	P-11A(1)	73.55	11.07	3.58	0.06	1.26	1.69	1.83	3.42	0.43	0.14	97.03	25.744	1.869
11	P-13(0)	76.25	9.82	2.79	0.05	0.91	1.82	1.95	3.42	0.56	0.12	97.69	17.536	1.754
12	P-13(1)	80.17	7.39	2.39	0.05	0.66	1.34	1.46	2.81	0.81	0.12	97.20	9.123	1.925
13	P-15(0)	77.45	8.32	2.78	0.06	0.86	1.77	1.71	2.79	0.64	0.15	96.53	13.000	1.632
14	P-15(1)	76.52	7.42	4.67	0.13	1.03	2.42	1.14	2.13	2.82	0.40	98.68	2.631	1.868
15	P-16(0)	72.38	11.26	3.94	0.09	1.15	2.30	1.91	3.60	0.70	0.15	97.48	16.086	1.885
16	P-16(1)	78.51	8.71	3.35	0.06	1.00	1.80	1.50	2.92	0.68	0.15	98.68	12.809	1.947
17	P-17/5 (0)	83.00	7.36	2.21	0.03	0.86	1.42	1.44	2.08	0.53	0.07	99.00	13.887	1.444
18	P-17/1	86.61	5.74	1.79	0.03	0.66	1.29	1.17	1.76	0.59	0.06	99.70	9.729	1.504
19	P-18/0 (0)	84.98	6.67	1.71	0.02	0.58	1.21	1.40	2.11	0.37	0.06	99.11	18.027	1.507
20	P-18/1	83.28	7.91	1.55	0.02	0.46	0.95	1.74	2.54	0.28	0.06	98.79	28.250	1.460
21	P-19/3 (0)	83.78	7.14	1.96	0.02	0.60	1.05	1.43	2.13	0.42	0.07	98.60	17.000	1.490
22	P-19/2	84.21	7.48	1.35	0.01	0.46	1.02	1.73	2.46	0.21	0.05	98.98	35.619	1.422
23	P-20/1	84.95	6.50	1.81	0.04	0.67	1.33	1.51	2.11	0.77	0.05	99.74	8.442	1.397
24	P-20/3	84.83	6.98	1.56	0.02	0.45	1.02	1.68	2.36	0.29	0.04	99.23	24.069	1.405
25	P-21/1	84.63	7.17	1.30	0.01	0.48	0.96	1.40	2.37	0.28	0.06	98.66	25.607	1.693
26	P-21/3	87.25	6.15	0.96	0.00	0.19	0.62	1.53	2.49	0.08	0.05	99.32	76.875	1.627
27	P-22/1	88.52	5.17	1.19	0.01	0.46	0.92	1.23	1.80	0.27	0.03	99.60	19.148	1.463
28	P-22/3	85.67	7.04	0.97	0.01	0.32	0.86	1.66	2.59	0.17	0.05	99.34	41.412	1.560
29	P-23/1	80.76	7.58	3.16	0.08	1.06	2.07	1.40	2.10	1.52	0.09	99.82	4.987	1.500
30	P-23/3	77.14	9.81	3.37	0.06	1.29	1.90	1.83	2.51	0.79	0.11	98.81	12.418	1.372
31	P-24/1	81.62	7.80	2.47	0.05	0.85	1.72	1.69	2.26	1.02	0.09	99.57	7.647	1.337
32	P-24/5	81.96	7.45	2.59	0.06	0.94	1.87	1.44	2.17	0.99	0.09	99.56	7.525	1.507
33	P-25/1	81.81	6.50	3.36	0.09	1.14	2.15	1.34	1.93	1.72	0.08	100.12	3.779	1.440

Sl No	SampleNo	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (T)(%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	Total	Al_2O_3/TiO_2	K_2O/Na_2O
34	P-25/3	84.27	6.85	1.80	0.04	0.68	1.41	1.50	2.22	0.55	0.06	99.38	12.455	1.480
35	PASS	62.8	18.9	6.5	0.11	2.2	1.3	1.2	3.7	1	0.16	97.87	18.900	3.083

Table 3. *Major oxides concentration Near shore samples from Rasulpur to Subarnarekha River Mouth (in wt %).*

SL NO	Sample No	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (T)(%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	Total	Al_2O_3/TiO_2	K_2O/Na_2O
1	BS-05	54.34	17.18	7.62	0.14	3.09	2.04	0.82	3.67	1.03	0.15	90.08	16.680	4.476
2	BS-19	56.61	16.99	6.40	0.11	3.11	2.49	0.96	3.50	0.98	0.15	91.30	17.337	3.646
3	BS-28	54.95	17.48	6.73	0.12	3.06	2.20	1.14	3.49	1.04	0.14	90.35	16.808	3.061
4	BS-39	51.97	17.84	8.54	0.13	3.27	1.53	0.77	3.74	1.06	0.15	89.00	16.830	4.857
5	BS-45	55.37	16.79	7.17	0.13	3.06	2.00	0.89	3.65	1.03	0.15	90.24	16.301	4.101
6	BS-51	53.97	17.56	7.71	0.13	3.20	1.82	0.85	3.77	1.03	0.14	90.18	17.049	4.435
7	BS-68	51.86	17.36	9.06	0.14	3.27	1.29	0.79	3.84	1.06	0.14	88.81	16.377	4.861
8	BS-35	53.81	17.74	7.81	0.12	3.14	1.86	0.92	3.59	1.03	0.14	90.16	17.223	3.902
9	BS-01	65.63	13.50	5.21	0.12	2.56	3.66	1.19	2.54	1.61	0.20	96.22	8.385	2.134
10	BS-01	73.44	11.77	4.43	0.09	1.20	1.85	1.87	2.93	2.36	0.11	100.05	4.987	1.567
11	BS-10	83.35	8.25	1.43	0.02	0.55	1.10	1.70	2.47	0.55	0.04	99.46	15.000	1.453
12	BS-22	84.84	6.35	2.60	0.02	0.32	0.84	1.47	2.21	0.46	0.06	99.17	13.804	1.503
13	BS-37	78.20	10.92	1.67	0.03	0.81	1.76	2.39	2.83	0.74	0.03	99.38	14.757	1.184
14	BS-43	79.66	9.61	2.41	0.03	0.85	1.50	1.84	2.43	0.78	0.07	99.18	12.321	1.321
15	BS-47	86.62	6.23	1.18	0.02	0.50	0.93	1.44	2.27	0.22	0.05	99.46	28.318	1.576
16	BS-52	83.30	6.92	2.30	0.06	0.78	1.74	1.46	2.12	1.09	0.03	99.80	6.349	1.452
17	BS-61	73.77	11.31	3.78	0.08	1.10	2.20	2.19	3.26	1.96	0.05	99.70	5.770	1.489
18	BS-66	77.88	8.77	3.99	0.10	1.04	2.12	1.62	2.38	2.46	0.05	100.41	3.565	1.469

The trace element compositions are quite variable but still comparable with the average compositions documented by [37, 40]. In the studied onshore sediments, the contents of large ion lithophile elements (LILE) like Ba and Sr vary from 393 to 717 ppm, 77 to 138 ppm, with an average of 567 ppm and 100.1 ppm respectively. The content of High Field Strength Elements (HFSE) like Y ranges from 80 to 8 ppm with an average of 28.04 ppm. Similarly, transition trace elements (TTE) like Sc, V, Cr, Ni, and Zn range from 4 to 12 ppm, 21 to 97 ppm, 36 to 370 ppm, 9 to 47 ppm, and 10 to 52 ppm with an average of 6.5 ppm, 56.0 ppm, 147 ppm, 26.0 ppm, and 30.0 ppm respectively (Table 4; Figure 7). In the nearshore sediments, the contents of large ion lithophile elements (LILE) like Ba and Sr vary from 410 to 801 ppm, 84 to 176 ppm, with an average of 577 ppm and 118 ppm respectively. The content of high field strength elements (HFSE) like Y ranges from 4 to 79 ppm with an average of 30.46 ppm. Similarly, transition trace elements (TTE) like Sc, V,Cr, Ni and Zn range from 4 to 24 ppm, 20 to 189 ppm, 17 to 276 ppm, 7 to 72ppm and 20 to 124 ppm with an average of 11 ppm, 88.5 ppm, 128.16 ppm and 31.6 ppm, 46.54 ppm, respectively (Tables 4, 5; Figure 8). The total trace element content is slightly higher in nearshore sediments (1476 ppm) than in onshore sediments (1395 ppm). For the studied samples, the higher concentration of Ba may indicate the presence of felsic rocks, in association with K and Sr. The enrichment of K and Sr may be due to the effect of potash metasomatism, where Ca has been leached out, replacing K within the feldspar lattice in association with Sr. The low concentrations of Cu, Co, Ni, and

Ga indicate the absence of ferromagnesian minerals in the source [27, 33, 40], which is reflected by the absence of mafic and ultramafic rocks in the source terrain.

Table 4. *Trace Elements concentration of Onshore samples from Rasulpur to Subarnarekha River Mouth (Results are in ppm).*

SL NO	Sample No	Ba	Co	Cr	Cu	Ga	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Zr	Total	Zr/Sc
1	P-1(1)	553	16	136	16	10	10	42	24	8	111	64	21	52	440	1503	55
2	P-1(0)	435	12	132	12	10	14	28	18	7	96	63	31	51	365	1274	52
3	P-5(1)	644	12	248	7	8	29	47	23	6	83	87	72	46	887	2199	148
4	P-5(0)	393	8	142	11	7	16	19	12	10	77	65	40	35	557	1392	56
5	P-7(1)	519	8	166	13	7	19	19	16	5	92	63	43	37	782	1789	156
6	P-7(0)	562	13	177	11	9	18	43	18	12	93	84	39	40	486	1605	41
7	P-10(1)	641	10	230	<1	5	5	26	41	7	111	61	25	31	189	1382	27
8	P-10(0)	630	13	208	<1	9	15	23	33	8	138	79	45	44	507	1752	63
9	P-11A(1)	674	10	146	<1	5	3	14	44	8	129	52	11	27	50	1173	6
10	P-11A(0)	546	11	158	<1	7	7	13	27	8	109	72	30	41	225	1254	28
11	P-13(1)	613	8	195	11	6	12	41	15	7	78	45	21	26	400	1478	57
12	P-13(0)	696	7	154	12	7	8	34	15	5	83	47	16	25	201	1310	40
13	P-15(1)	717	13	370	4	7	36	37	19	10	85	97	80	50	1502	3027	150
14	P-15(0)	607	10	117	14	6	11	26	14	6	79	48	21	25	281	1265	47
15	P-16(1)	588	9	164	13	6	11	45	15	6	77	55	19	27	213	1248	36
16	P-16(0)	683	11	169	13	8	11	38	17	5	97	55	21	29	256	1413	51
17	P-17/5 (0)	473	6	57	3	7	9	15	15	5	114	40	18	17	211	990	42
18	P-17/1	438	1	73	1	6	8	11	13	4	96	38	17	13	245	964	61
19	P-18/0 (0)	490	4	51	4	7	8	13	17	4	114	29	12	10	136	899	34
20	P-18/1	564	5	45	11	7	6	9	22	4	126	25	12	10	136	982	34
21	P-19/3 (0)	471	4	54	6	7	9	10	16	4	104	33	15	12	169	914	42
22	P-19/2	523	2	36	3	7	6	11	17	4	126	21	8	10	84	858	21
23	P-20/1	487	4	84	2	6	10	11	15	5	114	45	19	13	301	1116	60
24	P-20/3	542	5	50	1	8	7	10	18	4	118	27	9	10	124	933	31
25	P-21/1	540	4	75	7	7	6	16	12	4	110	25	6	10	95	917	24
26	P-21/3	554	2	17	1	5	5	7	15	4	113	20	11	10	63	827	16
27	P-22/1	410	1	46	1	5	6	9	10	4	84	26	15	10	91	718	23
28	P-22/3	572	1	42	2	5	5	9	13	4	122	20	4	10	75	884	19
29	P-23/1	557	5	149	10	10	16	17	34	5	131	71	41	32	607	1685	121
30	P-23/3	584	12	87	26	9	11	28	23	7	153	58	24	33	301	1356	43
31	P-24/1	560	6	106	17	9	12	15	25	5	136	54	30	40	430	1445	86
32	P-24/5	522	8	115	4	8	12	15	20	7	133	59	24	22	342	1291	49
33	P-25/1	521	7	183	6	8	15	19	19	8	118	75	45	39	558	1621	70
34	P-25/3	520	7	62	2	7	8	12	21	6	122	36	15	14	170	1002	28

SL NO	Sample No	Ba	Co	Cr	Cu	Ga	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Zr	Total	Zr/Sc
35	PASS	650	-	110	28	17.5	19	55	20	16	200	150	27	67	210	1570	13

Table 5. *Trace Elementsconcentration of Nearshoresamples from Rasulpur to Subarnarekha River Mouth (Results are in ppm).*

SL NO	Sample No	Ba	Co	Cr	Cu	Ga	Nb	Ni	Pb	Sc	Sr	V	Y	Zn	Zr	Total	Zr/Sc
1	BS-05(G)	602	19	148	57	20	19	59	21	24	99	160	35	102	272	1637	11
2	BS-19(G)	604	21	143	61	21	19	61	26	20	100	155	34	103	260	1628	13
3	BS-28(G)	588	15	153	42	19	19	50	20	17	105	139	40	88	372	1667	22
4	BS-39(G)	476	14	186	19	12	22	30	27	12	133	118	69	56	927	2101	77
5	BS-45(G)	607	19	148	56	19	19	57	23	18	100	152	35	97	218	1568	12
6	BS-51(G)	617	18	150	55	21	19	62	24	18	100	163	32	108	185	1572	10
7	BS-68(G)	602	22	165	79	21	20	72	19	24	92	189	30	124	147	1606	6
8	BS-35(G)	585	15	134	43	19	18	50	23	18	107	133	39	85	342	1611	19
9	BS-01(G)	594	20	156	61	20	20	64	26	23	96	183	33	110	207	1613	9
10	BS-01	698	11	260	10	12	28	28	35	11	144	109	74	36	1389	2845	126
11	BS-10	565	4	85	2	9	9	10	19	6	126	38	21	10	269	1173	45
12	BS-22	505	5	130	13	8	7	25	20	4	110	43	16	12	288	1186	72
13	BS-37	658	7	99	7	11	13	21	19	8	169	47	16	12	235	1322	29
14	BS-43	537	8	102	5	11	12	17	20	7	142	50	22	15	314	1262	45
15	BS-47	525	4	60	1	6	6	11	19	4	110	23	13	10	86	878	22
16	BS-52	525	3	123	3	9	12	13	16	7	126	55	29	22	378	1321	54
17	BS-61	801	7	244	9	11	22	33	30	7	176	95	50	28	801	2314	114
18	BS-66	659	12	276	12	11	23	33	26	7	144	109	79	36	1283	2710	183
19	PASS	650	-	110	28	17.5	19	55	20	16	200	150	27	67	210	1570	13

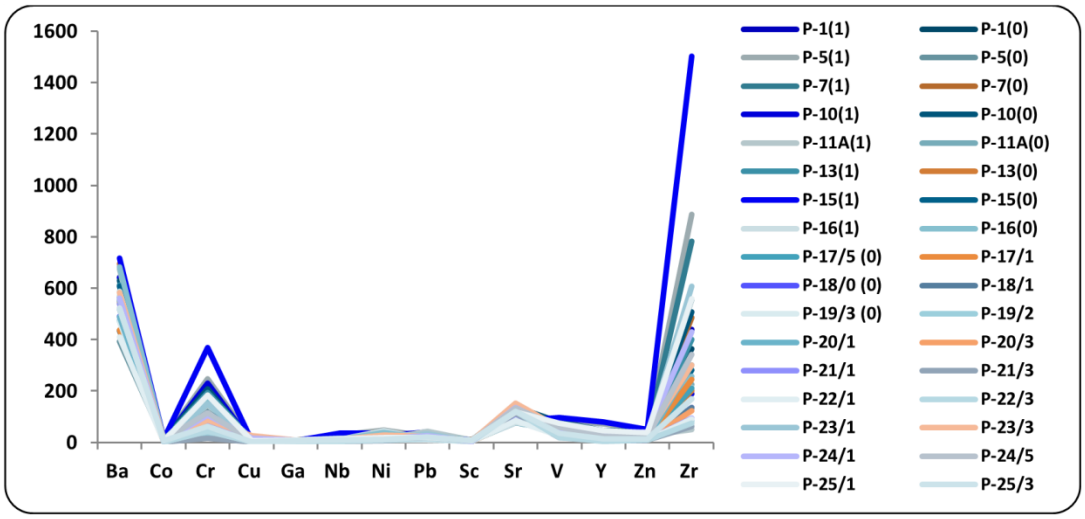

Figure 7. *Concentration of Trace Elements of surface sediments samples for (3) Onshore and (4) Near shore sediment from Rasalpur to Subarnarekha River Mouth.*

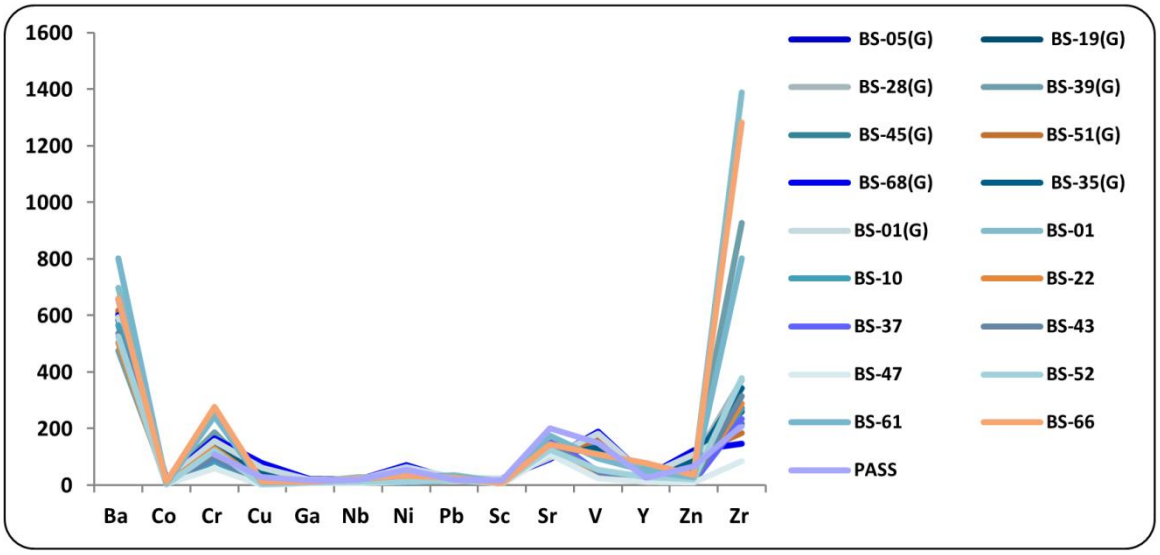

Figure 8. *Concentration of Trace Elements of surface sediments samples for (3) Onshore and (4) Near shore sediment from Rasalpur to Subarnarekha River Mouth.*

In order to compare sediments of different geomorphic domains, Al_2O_3 is used as a normalization factor as it is immobile in nature during diagenesis and metamorphism [7]. Major oxides of the studied onshore and nearshore samples were plotted against Al_2O_3 as depicted in Figure 9 In addition, average PAAS (Post-Archaean Australian Shale) values were extracted [37, 40], respectively, and included in the plots for comparison purposes. Based on the average values, the nearshore samples exhibit almost similar major oxide abundances relative to PAAS.

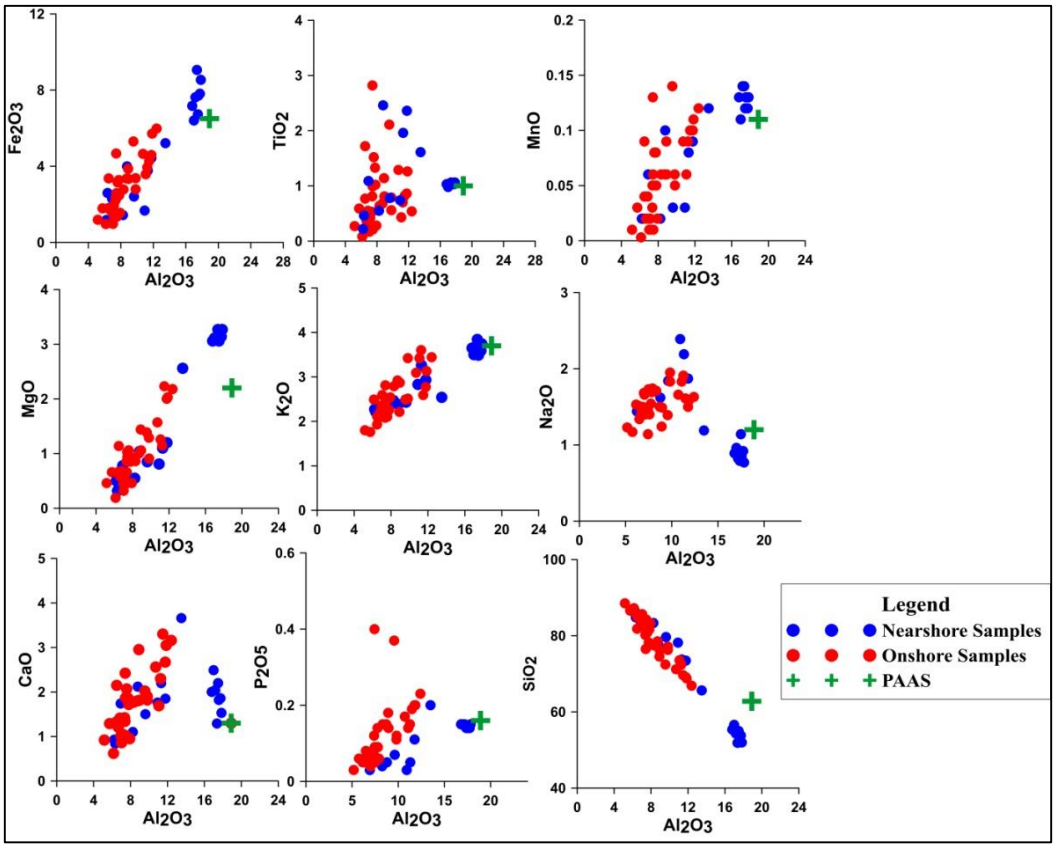

Figure 9. *Major Element vs Al_2O_3 bivariant plot showing distribution for Onshore and Near shore sediment from Rasulpur to Subarnarekha River Mouth.*

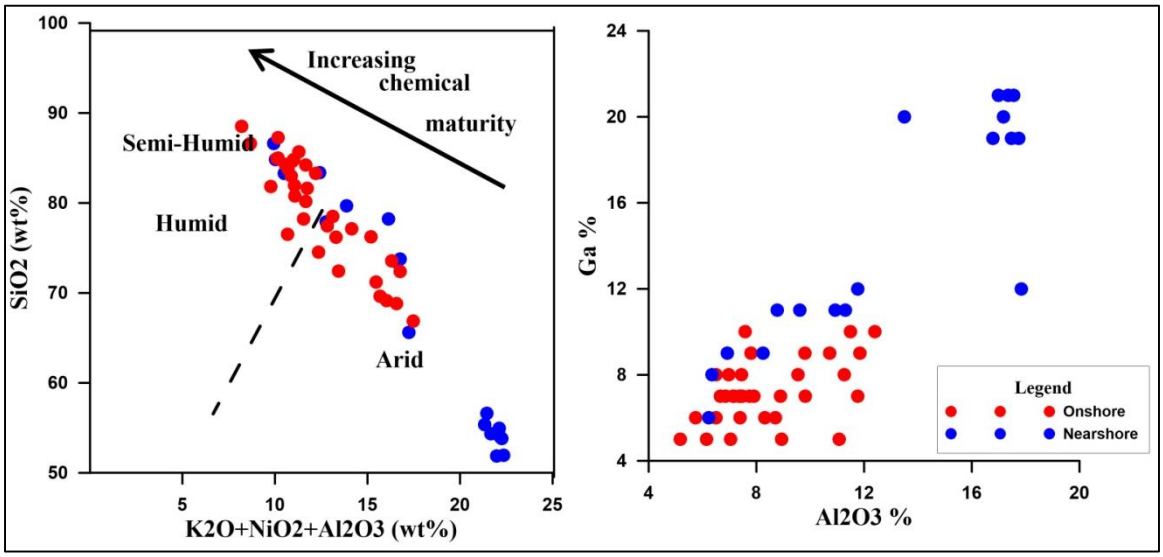

Figure 10. Plot of SiO_2 (reflective of quartz content) versus $K_2O+Na_2O+Al_2O_3$ (reflective of feldspar content), ii. Gavs Al_2O_3 bivariant plot showing distribution for Onshoreand Near shore sediment from Rasulpur to Subarnarekha River Mouth..

Onshore and offshore samples show a positive correlation between Fe_2O_3, MnO, K_2O, MgO, CaO and P_2O_5 with respect to Al_2O_3. The strong positive correlation of these major oxides with Al_2O_3 indicates that they are associated with micaceous/clay minerals. TiO_2 also shows positive correlation except for few samples. Whereas the strong negative correlation between SiO2 and Al_2O_3 indicates that the clay minerals in the clay fraction have been leached out during chemical weathering, whereas quartz has retained its composition due to its resistance to chemical weathering (Figure 9). At the same time, it is also noticed that there is no particular trend between Na_2O and Al_2O_3. The strong positive correlation between K_2O and Al_2O_3 may be because of the presence of K-feldspar and clay minerals such as illite within the sediments. The positive relationship between Ga and Al_2O_3 may be because of their occurrence together in feldspars and clay minerals (Figure 10).

2.2. Mineralogical Studies

Microtextures observed on anhedral (rounded, sub-rounded, and angular) quartz grains and the heavy minerals (Figure 11) suggest that the quartz grains and heavy minerals in the study area could be indicators of the action of dynamic agents and depositional processes, such as solution pits, etching, conchoidal fractures, irregular surfaces and depressions, linear and curved grooves, fracture planes, longitudinal cleavages, arcuate steps, and upturned plates, etc. (Figure 11). Solution pits and oriented etch pits are indications of chemical weathering, suggesting that the grains were present in marine environments for a long time, affecting older mechanical marks [39].

Rounded grains and regular surfaces are produced due to mechanical processes and are reworked grains. Conchoidal fractures and V forms (linear or curved) are probably produced due to grain-to-grain collision. Intensive reworking processes occurring in high-energy environments such as the surf zone of the beach cause angular conchoidal fractures widely developed on grain surfaces. Linear and curved grooves are used to infer the wave action [20]. The chemical marks appear as oriented etch pits and oriented Vs affecting previous mechanical textures as well. Arcuate steps and upturned plates, which are cited as indicative of eolian environments [21, 26].

EPMA analysis reveals the presence of heavy minerals (average 3.6% HM) comprising ilmenite and garnet as major constituents, followed by magnetite, sillimanite, sphene, epidote, hornblende, zircon, hypersthene, tourmaline, biotite, chlorite, and rutile. The mineral composition of garnet is almandine. The TiO_2 content determines the degree of alteration in ilmenite. Highly altered ilmenite has a higher percentage of TiO_2 (56.86%) [17]. Lower values of Al_2O_3 compared to MgO and MnO in each grain also confirm this (Frost et al., 1983). In ilmenite, the concentration of TiO_2 helps in determining whether it is derived from an igneous or metamorphic source. The igneous source has TiO_2 content ranging from 42% to 52%, whereas the metamorphic source has a mean value of TiO_2 of 51%. In this study area, the TiO_2 content ranges from 40.03% to 56.86%, suggesting the possibility of metamorphic ilmenite. The Subarnarekha River flows through the area, so the metamorphic associates from the nearby area could be the source of ilmenite. The ilmenite grains here are moderately altered since they show signs of alteration along grain boundaries, and the grains have angular edges. Chemical weathering may be another cause of alteration of these ilmenite grains. The considerably high values of FeO and Al_2O_3 in most of the garnets suggest that they are of almandine group. From EPMA, it may be concluded that altered ilmenite is the dominant type. It is the most abundant titanium-rich mineral in the study area, whereas almandine is the most abundant variety of garnet.

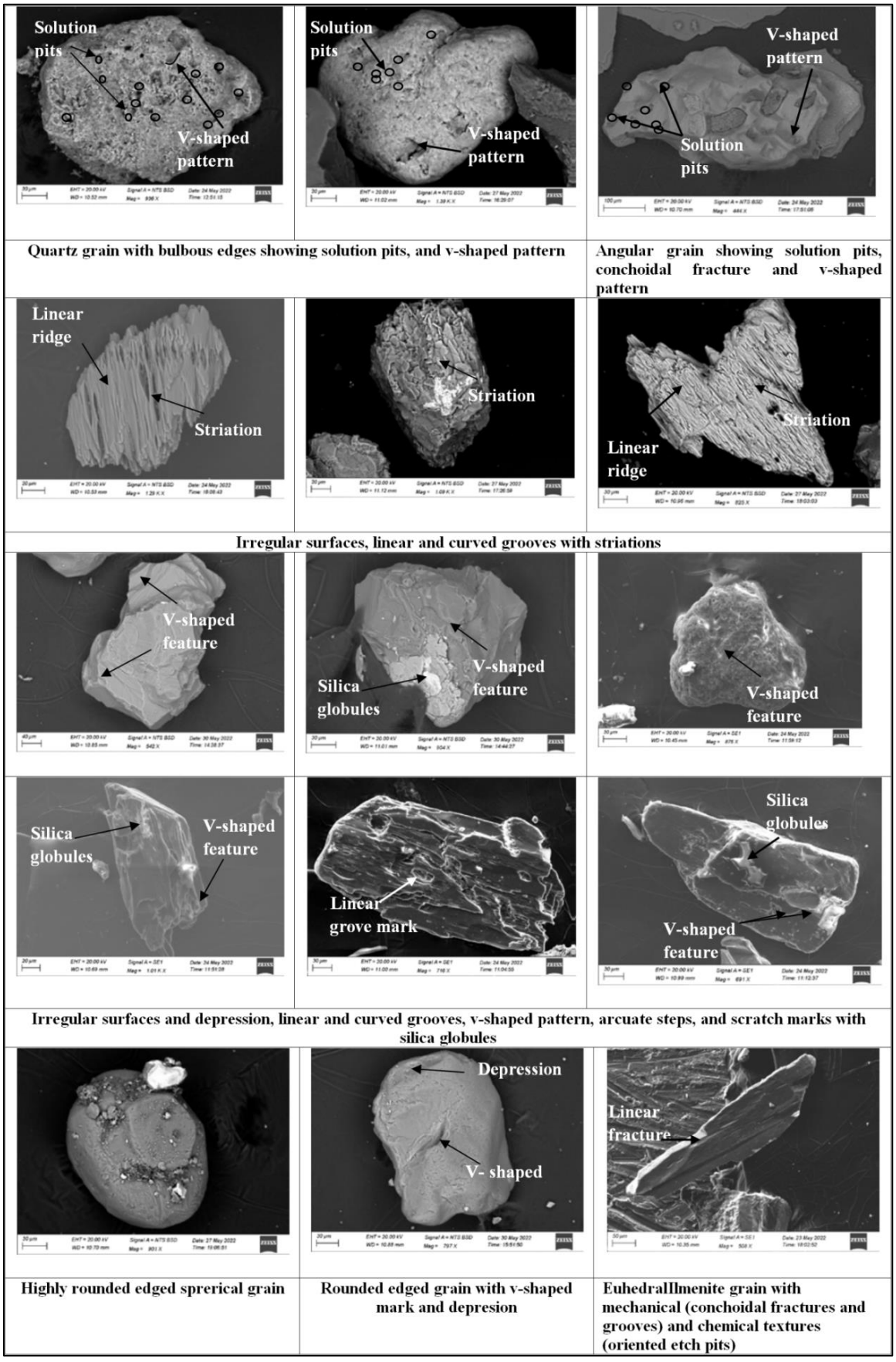

Figure 11. *Morphology, surface features and micro textures of grains from SEM-EDX images of the study area.*

2.3. Palaeo Weathering Conditions/ Weathering and Recycling and Depositional Environment

The use of major element geochemistry, in particular, should be treated with caution due to their possible mobility and redistribution during chemical weathering and diagenesis [26, 29]. However, it can be applied to determine the degree of alteration [16, 30, 42]. The chemical composition of the source rock, along with the duration of weathering and climatic conditions, plays a key role in defining the intensity of weathering. Several researchers around the world have documented that molecular proportions of mobile and immobile element oxides such as Na_2O, CaO, K_2O, and Al_2O_3 carry the signatures of the intensity of weathering [18, 31].

Different schemes of weathering indices proposed by various researchers such as the Chemical Index of Alteration (CIA) by [30], Plagioclase Index of Alteration (PIA) by [16], Weathering Index of Parker (WIP), Chemical Index of Weathering (CIW) by [18], and Index of Chemical Variability (ICV) by [36] are widely used. To decipher the degree of weathering, weathering indices like CIA and PIA are employed, and ICV is used to determine compositional maturity.

The Chemical Index of Alteration (CIA) was calculated using the following formula defined by [31]: CIA = $[Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO* represents the content of CaO incorporated in the silicate fraction. The value of CIA provides a measure of the ratio of original/primary minerals to secondary products such as clay minerals. CIA values range from almost 50 in the case of fresh rocks to 100 for completely weathered rocks. Thus, CIA values increase with increasing weathering intensity, reaching 100 when all the Ca, Na, and K have been leached from the weathering residue. CIA = 50-60 indicates incipient weathering, CIA = 60-80 indicates intermediate weathering, and CIA > 80 indicates extreme weathering [31]. The Index of Compositional Variability (ICV) was also calculated to assess the association of detrital mineralogy and to determine the maturity of the sediments [ICV = $(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO) / Al_2O_3$] [36] (Table 6). According to [36], the non-clay minerals have higher ICV values (pyroxenes and amphiboles have ICV values of 10–100), whereas the ICV value of feldspars ranges between 0.6 and 1, and clay minerals such as illite, montmorillonite, and kaolinite have ICV values of <0.3. Chemical Index of Weathering (CIW) is considered as a superior method consisting of a restricted number of components with consistent geochemical behavior during weathering. According to [18], CIW is expressed as CIW = $[Al_2O_3 / (Al_2O_3 + CaO + Na_2O)] \times 100$. According to [16], source area of weathering and elemental redistribution during diagenesis can be assessed by Plagioclase Index of Alteration (PIA=$[(Al_2O_3-K_2O)/(Al_2O_3+CaO+Na_2O-K_2O)] \times 100$). A maximum PIA value (100) indicate completely altered mineral such as kaolinite and gibbsite and weathered plagioclase has a PIA value of 50.

Table 6. Weathering Parameters of the Onshore samples from Rasulpur to Subarnarekha River Mouth.

SL NO.	Sample No	CIA	ICV	CIW	PIA	CIA/1CV
1	P-1(1)	60.107	1.331	72.135	43.432	45.144
2	P-1(0)	60.506	1.227	70.061	46.867	49.306
3	P-5(1)	61.812	1.333	73.688	45.696	46.371
4	P-5(0)	58.170	1.325	67.991	43.725	43.911
5	P-7(1)	57.836	1.283	69.507	41.045	45.093
6	P-7(0)	60.428	1.317	71.905	44.467	45.873
7	P-10(1)	59.166	1.188	73.039	40.172	49.807
8	P-10(0)	59.456	1.271	71.754	42.318	46.797
9	P-11A(1)	61.466	1.070	75.874	42.476	57.468
10	P-11A(0)	62.888	1.159	73.823	48.075	54.260
11	P-13(1)	56.846	1.179	72.522	35.231	48.231
12	P-13(0)	57.731	1.114	72.259	37.625	51.820
13	P-15(1)	56.598	1.553	67.577	40.351	36.455
14	P-15(0)	57.025	1.198	70.508	37.903	47.588
15	P-16(1)	58.339	1.220	72.523	38.781	47.802
16	P-16(0)	59.046	1.154	72.786	40.168	51.182

SL NO.	Sample No	CIA	ICV	CIW	PIA	CIA/1CV
17	P-17/5 (0)	59.837	1.092	72.016	42.927	54.777
18	P-17/1	57.631	1.167	70.000	39.960	49.373
19	P-18/0 (0)	58.560	1.054	71.875	40.035	55.561
20	P-18/1	60.198	0.918	74.623	40.868	65.587
21	P-19/3 (0)	60.766	1.007	74.220	42.638	60.343
22	P-19/2	58.944	0.940	73.118	39.559	62.717
23	P-20/1	56.769	1.149	69.593	38.341	49.397
24	P-20/3	57.973	1.016	72.107	38.372	57.074
25	P-21/1	60.252	0.909	75.236	40.336	66.259
26	P-21/3	56.997	0.942	74.096	33.920	60.510
27	P-22/1	56.689	1.085	70.628	36.952	52.242
28	P-22/3	57.942	0.911	73.640	36.626	63.637
29	P-23/1	57.643	1.302	68.597	41.673	44.269
30	P-23/3	61.121	1.117	72.452	45.483	54.708
31	P-24/1	57.906	1.159	69.581	41.128	49.964
32	P-24/5	57.618	1.217	69.238	40.835	47.327
33	P-25/1	54.530	1.540	65.065	38.339	35.409
34	P-25/3	57.179	1.117	70.184	38.648	51.199
35	PASS		0.850			

Table 7. *Weathering Parameters of the Nearshore samples from Rasulpur to Subarnarekha River Mouth.*

SL NO	Sample No	CIA	ICV	CIW	PIA	CIA/1CV
1	BS-05(G)	72.459	1.012	85.729	56.980	71.625
2	BS-19(G)	70.969	0.975	83.121	56.349	72.768
3	BS-28(G)	71.905	0.958	83.958	57.548	75.083
4	BS-39(G)	74.707	1.008	88.580	59.045	74.125
5	BS-45(G)	71.967	1.007	85.315	56.322	71.499
6	BS-51(G)	73.167	0.995	86.802	57.458	73.502
7	BS-68(G)	74.570	1.059	89.300	58.076	70.394
8	BS-35(G)	73.579	0.983	86.452	58.689	74.845
9	BS-01(G)	64.624	1.132	73.569	52.465	57.096
10	BS-01	63.898	1.051	75.985	47.991	60.799
11	BS-10	61.021	0.881	74.661	42.751	69.246
12	BS-22	58.418	1.175	73.326	38.086	49.725
13	BS-37	61.006	0.869	72.462	45.196	70.198
14	BS-43	62.484	0.943	74.208	46.684	66.277
15	BS-47	57.314	1.018	72.442	36.431	56.319

SL NO	Sample No	CIA	ICV	CIW	PIA	CIA/1CV
16	BS-52	56.536	1.223	68.379	39.216	46.245
17	BS-61	59.652	1.115	72.038	42.458	53.502
18	BS-66	58.899	1.283	70.104	42.915	45.915

The average CIA value for the studied onshore samples is 60.0, and for the nearshore samples, it is 64.0 (Tables 6, 7). The average CIA value is higher for nearshore region samples. This clearly points towards intense to intermediate weathering in the source area for both onshore and nearshore sediments [31]. Similarly, the average CIW values of the studied onshore samples are 72.0, and for the nearshore samples, it is 77.15 (Tables 6, 7), indicating moderate to high weathering for both regions. The CIW index values are higher than CIA values for the analyzed samples due to the exclusion of K_2O from the index. The PIA values of the onshore and nearshore samples range from 48.0 to 35.0 and 60.0 to 40.0 (Tables 6, 7) with an average of 41.56 and 46.63, respectively, suggesting moderate destruction of feldspars during source weathering, transport, sedimentation, and diagenesis. A maximum PIA value indicates completely altered minerals such as kaolinite and gibbsite, and weathered plagioclase has a PIA value of 50 (Tables 6, 7).

Furthermore, plotting of CIA vs. ICV after [23] for the studied onshore (average 60) and nearshore (average 64) samples shows that the samples of both geomorphological domains are immature in nature and have suffered intense to moderate weathering (Tables 6, 7; Figure 12). CIA measures the degree of alteration of feldspar to clay minerals during weathering; accordingly, Ca, Na, and K are largely removed by soil solution and increase the relative proportion of Al in the sediments, thus leading to higher CIA values [31]. If CIA is higher and ICV low, then the cause could be either high weathering of the source or recycling of previously weathered material [31]. The CIW index values are higher than CIA values for the analyzed samples due to the exclusion of K_2O from the index.

Besides, the high ratio of Zr/Sc indicates the enrichment of zircon, thus suggesting sediment recycling (Tables 6, 7).

The bivariate plot (Figure 9) of SiO_2 (reflective of quartz content) vs $Al_2O_3 + K_2O + Na_2O$ (reflective of feldspar content) represents the chemical maturity trend as a function of climate, as proposed by [44]. The onshore samples revealed semi-arid to semi-humid climatic conditions, whereas nearshore samples mostly show arid to semi-humid conditions in the area from various sources tending towards increasing chemical maturity. Overall, the investigated samples of the study area showed variable degrees of chemical maturity extending from low to intermediate levels. The beach sands plotted in the semi-arid region may have experienced little or no chemical weathering and are far less mature than those plotted in the semi-humid area.

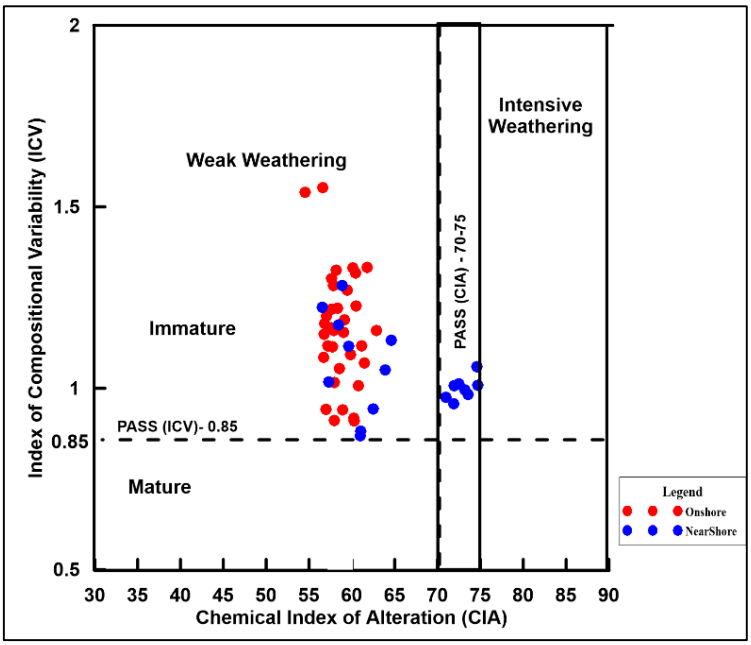

Figure 12. *ICV-CIA plot (after Long et al., 2012b) for Onshore and Near shore sediment from Rasulpur to Subarnarekha River Mouth.*

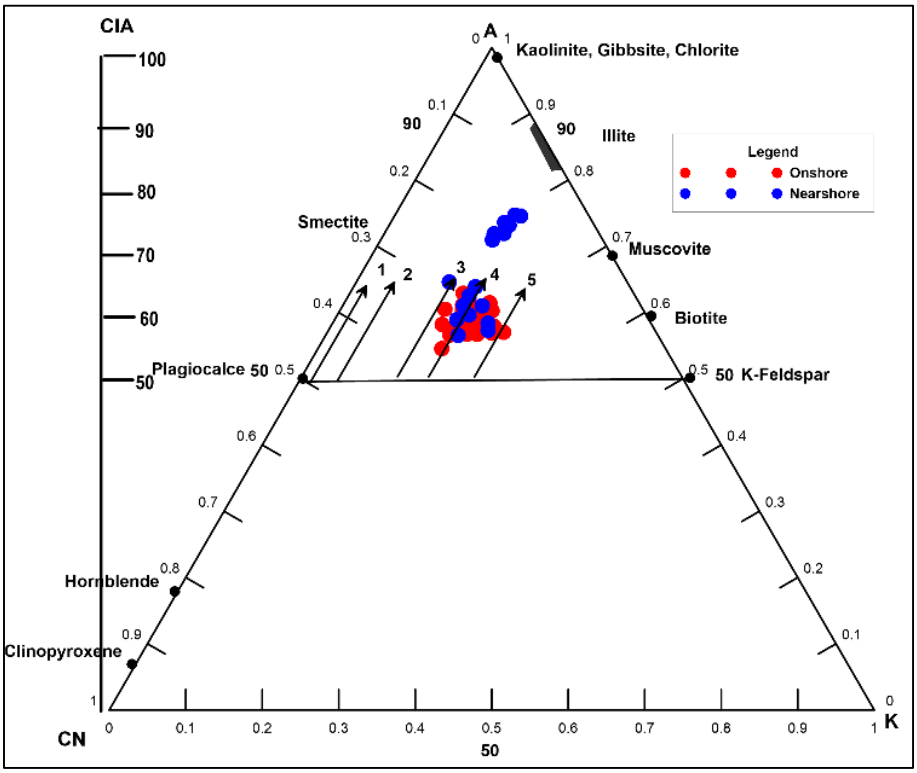

Figure 13. *A-CN-K (Al_2O_3-CaO*+ Na_2O-K_2O) Ternary Diagram (Nesbitt and Young, 1984) for Onshore and Near shore sediment from Rasulpur to Subarnarekha River Mouth are also shown. (Numbers 1-5 denote trends of initial weathering profiles of various rock types: 1. Gabbro; 2. Tonalite: 3. Diorite; 4. Granodiorite; 5. Granite).*

The Ternary plot of A-CN-K [30] was used to assess the composition of the source rock as well as the mobility of the element. The A-CN-K diagram (Tables 6, 7; Figure 13) is a more useful way of evaluating the chemical weathering trend compared to the CIA index [30, 38]. In the A-CN-K plot, the samples are plotted above the line joining plagioclase and potash feldspar, indicating moderate to intense chemical weathering in the source area [30]. The samples also show a linear trend parallel to the A-CN axis. The nearshore samples (collected from Rasalpur to Mandarmani area) show a linear trend towards illite on the A-K edge and do not show any inclination towards the K apex, which indicates the presence of more illite than other clay minerals like kaolinite and smectite. The inclination towards illite is interpreted to be the effect of potash metasomatism, where post-depositional processes convert kaolinite to illite; however, there is no conversion trend observed toward K_2O. From the ternary diagram, the onshore and nearshore sediments mostly plot between the average granite and diorite line, suggesting the protolith of the area to be of intermediate to felsic source rocks. The sediment maturity can also be determined with the help of the SiO_2/Al_2O_3 ratio, where a ratio >5 indicates mature sediments, while a ratio <5 is an indication of immaturity [34, 35]. The value of SiO_2/Al_2O_3 in the studied onshore samples ranges from 5.4 to 17.12 (average = 10.1), and nearshore samples range from 3 to 14 (average = 6.5), indicating immature character to progressive maturity of sediments [32, 35]. The values of the K_2O/Na_2O ratio range from 1.34 to 2.11 (average = 1.64).

SEM studies indicate a number of micro features formed during different stages of transportation and deposition. Impact features were produced due to physical activity in the nearshore zone. Occasional contact with seawater caused chemical reactions resulting in various etch features, sometimes controlled by the properties of the grain. Perfect rounding of some grains indicates a long transport history. V forms are associated with grains from the beach and indicate a longer period and higher intensity of subaqueous agitation. Chemical abrasion produces solution pits and etch marks. Rounded grains, regular surfaces are produced due to mechanical processes and are reworked grains [28, 29]. Quartz, garnet, and ilmenite grains with irregular outlines as observed from SEM are derived from nearby sources, as irregular surfaces indicate a lesser degree of transportation. Few rounded grains of quartz are also observed, which have been produced from the well transportation of the grains [4]. These grains are probably derived from a nearby crystalline source. Intense wave action is also scavenging the grains from the seawall. Moreover, the area is cyclone-prone, so the sand dunes in the upper foreshore zone are undergoing mechanical abrasion in the aeolian and aqueous environment. The various microfeatures have been produced by different processes in different environments [41]. Wave action and aqueous collision result in grain fracturing, mechanical impact, weathering and removal of blocks,

grinding, chemical action, dissolution, and precipitation. Medium to high-energy depositional environments prevail in the area. Mixing of these features suggests that the minerals present in the beach sand have undergone mechanical abrasion in the aeolian environment due to the collision of grains, producing conchoidal features.

3. Provenance

The dominance of SiO_2 in the sediments is a result of the presence of free quartz derived from the felsic-dominated terrain. Al_2O_3/TiO_2 ratios of the sediments can indicate their source rocks based on these elements associated with felsic and mafic minerals, respectively [19] depending on the abundance of the Al_2O_3/TiO_2 ratio. Aluminum is hosted in feldspars, while titanium is in mafic minerals (olivine, pyroxene, hornblende, biotite, and ilmenite). Aluminum and titanium are stable during weathering, accumulate as residues, and remain constant during surficial weathering, volcanic processes, hydrothermal alteration, etc. The ranges of Al_2O_3/ TiO_2 ratios such as 3–8, 8–21 and 21–70 suggest mafic, intermediate and felsic igneous source rocks, respectively [19, 25, 33]. The relative increase in the Al_2O_3/ TiO_2 ratio in onshore and nearshore sediments are 14.40 and 18.5 respectively suggested they are derived from mainly intermediate to felsic source rocks. The concentration of TiO_2 in Ilmenite ranges from 40.03 to 56.86% (avg-52%), depicting a metamorphic signature with an igneous source.

The combination of mineralogical and surface texture analysis (SEM-EDX) of grains has permitted the detection of a long history of mechanical andchemical processes generated during several stages and at different depositional environments. Several depositional stages were identified: the oldest corresponds to eolian environments, followed by energetic fluvial and coastal processes. Another younger stage is shown by chemical alterations acquired in marine environments, and is characterized by dissolution processes that affected old mechanical marks.

Based on the presence of the heavy mineral assemblages, the provenance of sediment indicates a mixed igneous and metamorphic source. Chotonagpur granite gneiss and Rajmahal traps are contributing Khondalites of the Eastern Ghats. The northernmost extension of the Eastern Ghats, i.e., the Nilgiri mountainous region of Odisha, is also a major contributor of heavy minerals through its khondalitic and gneissic provinces, as this is the nearest exposure from the confluence point of the Subarnarekha River.

4. Conclusion

The dominance of SiO_2 in the sediments is a result of the presence of free quartz derived from the felsic-dominated terrains. In addition, the strong negative correlation between the SiO_2 and Al_2O_3 shows that the variation in the chemical composition is in response to relative abundance of mineral quartz (in silt size fraction) and clay minerals in clay fraction. The strong positive correlation between the K_2O and Al_2O_3 may be because of the presence of K-feldspar and clay minerals such as illite within the sediments, which is also supported from the K_2O/Na_2O ratio. TiO_2 is low and consistent in the sediments contributed by a felsic-dominated recycled orogenic provenance. Trace-element concentrations in sediments result from the competing influence of provenance, weathering, diagenesis and sediment sorting [9]. Elevated Ba values may indicate the presence of felsic rocks, in association with K and Sr. The enrichment of K and Sr may be due to the effect of potash metasomatism where Ca has been leached out, replacing K within the feldspar lattice in association with Sr. The CIA, PIA value, and A-CN-K diagram reveal the paleo weathering condition of the source terrain, which is affected by intense to moderate weathering/intermediate weathering. Based on all geochemical data and various plots, it is evident that the samples from the nearshore area have undergone more weathering than the onshore samples. Furthermore, the ICV value, the plot of CIA vs. ICV, and the ratio of SiO_2/Al_2O_3 indicate mineralogical immaturity to progressive maturity of the sediments. Based on the mineralogical assemblage, it can be concluded that the sediments are derived from a mixed igneous and metamorphic source. The different types of microtextures exhibited by the sediments suggest that they result from mechanical, chemical, or mixed processes and are produced by various transportation processes under different environmental conditions.

Abbreviations

XRF	X-ray Fluorescence Spectrometry Technique
ICV	Index of Compositional Variability
CIA	Chemical Index of Alteration
CIW	Chemical Index of Weathering Results
PIA	Plagioclase Index of Alteration

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Author Contributions

Priyanka Dey Guha: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Data Availability Statemant

The data which have been used for the manuscript were generated in the Field Item -129 of Geological Survey Of India and posted to a trusted repository, and the data repository is allowing journal and reviewer access to posted data.

Conflicts of Interest

The authors declare no conflicts of interest.

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