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Identification of grain size and mineral distributions in the surface sediments of Red river estuaries in Vietnam

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Abstract:

The mineral composition and grain size of 45 surface sediment samples from the estuaries of the Red River system were analysed to assess the dynamics and origin of the sediments. Five types of sediments are distributed in river mouths, which are coarse silt, very fine sand, very coarse silt, fine sand, and medium silt. The mineral contents in the sediment were as follows: quartz 46.0%, illite 18.3%, kaolinite 11.8%, chlorite 6.4%, feldspar 6.0%, goethite 4.4%, calcite 1.9%, gibbsite 1.7%, and amphibole 1.4%. Between grain size parameters and mineral compositions were positive and negative correlations. The positive correlations were between S0 and illite, kaolinite, goethite, calcite; between Md and quartz, feldspar, amphibole; between illite, kaolinite, chlorite, goethite together. The negative correlations were between quartz, feldspar, Md with illite, kaolinite, chlorite; between goethite with quartz, feldspar, Md; between amphibole with kaolinite; between gibbsite with quartz; between S0 and Md, quartz, feldspar, amphibole. There were two sediment groups: Group 1 was weakly dynamic, and Group 2 was strongly dynamic. The minerals in the sediments were mainly continental, characterised by illite, kaolinite, chlorite, quartz, feldspar, and amphibole, with other sources, including precipitation and weathering, being limited.

Keywords: **coast, estuary, minerals, Red river, sediments, Vietnam.**

Classification numbers: **4.2, 5.1, 5.3**

Highlights

• Grain sizes and minerals were examined in estuaries and coastal areas of the Red river system.

• The common sediment types included coarse silt, very fine sand, very coarse silt, fine sand, and medium silt.

• The mineral contents were as follows: quartz 46.0%, illite 18.3%, kaolinite 11.8%, chlorite 6.4%, feldspar 6.0%, goethite 4.4%, calcite 1.9%, gibbsite 1.7%, and amphibole 1.4%.

• Two sediment groups exhibited weak and strong dynamics.

• The minerals were predominantly continental, with limited precipitation and weathering sources.

1. Introduction

The Red river, originating on the Tibet-China Plateau, flows into Vietnam's coastal region and has a catchment area of 160,000 km^2 [1]. Sedimentation rates in coastal regions were determined using the isotopes ^{210}Pb, ^{234}Th, ^{226}Ra, and ^{137}Cs. In the prodelta, the rate varies from 1.5 to 2.1 cm/year [2]. At a depth of 20 m, the rate was 0.63 cm/year, whereas at a depth of 10 m, it was 1.03 cm/year [3]. In the intertidal zone, the rate ranges from 0.34 to 3.04 cm/year [4, 5].

Sediment movement in coastal areas is influenced by the monsoon season and land-ocean interactions. At depths of 10-30 m, sediment movement is predominantly in the southwest direction [6]; at a depth of 10 m to the coast, the direction is southwest, southeast, and east during the northeast monsoon season and northeast during the southwest monsoon season. The sediment supply from rivers has declined significantly due to the construction of the Hoa Binh dam, altering the sediment balance along the coast and causing erosion at the Hai Hau coast [7-9].

The Ba Lat estuary predominantly contains fine sediment, consisting of clay, silty clay, and sandy silty clay, accounting for 70-85% of the total sediment. The mineral composition includes quartz (57-90%), rock fragments (10-35%),

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feldspar, and mica (1-15%). On the erosion coast, heavy minerals include magnetite, ilmenite, amphibole, and zircon. Ilmenite is mostly concentrated in intertidal areas. At the accumulation coast, clay minerals, including illite, kaolinite, montmorillonite, and chlorite, are common [10]. The Hai Hau coast has four types of sediments: fine sand, very fine sand, very coarse silt, coarse silt, and medium silt. The heavy mineral content decreases in the following order: beach cliff, high beach, low beach, and submersible [11]. Light minerals are divided into three groups: the northern group, the middle group, and the southern group [12].

The total suspended solids (TSS) from river discharge to the coast decreased after the Hoa Binh dam was built. Data from 1960 to 2010 revealed significant fluctuations; from 1960 to 1979, the TSS was approximately 77.3×10^6 tons/year, which decreased to 30.5×10^6 tons/year from 1989 to 2010 [9]. Sediment from the Red river estuary significantly impacts the coast, both locally and offshore in the Gulf of Tonkin. The presence of smectite in Ha Long Bay indicated that it originated from the Red river [13]. The Gulf of Tonkin's surface sediments have four identified sources based on clay minerals: southern mainland China, Hainan Island, the Red river system, and the mouth of the Gulf of Tonkin [14].

Clay minerals can adsorb organic matter, with illite capable of adsorbing organic matter of all sizes, whereas chlorite adsorbs organic matter larger than 16 µm [15]. When clay minerals are used, it is possible to identify traces of environmental changes and behaviour [16]. Clay minerals such as montmorillonite and kaolinite can adsorb organic matter, and organic matter can adsorb iron ions that are common in the environment on the surface of clay minerals [17]. In estuaries, the composition of fine-grained matter depends on the biological world, human impacts, and deflocculation and flocculation processes [18]. Grain size is an important factor affecting porosity and stress sensitivity in both rocks and sediments [19] and is a crucial geotechnical characteristic affecting the properties of sediments. Mineral compositions can be used to identify diagenesis stages [20].

Previous studies on grain size and mineral composition in Red river estuaries were not systematic and did not cover the entire estuaries. This study aims to understand the origin and dynamics of these estuaries by examining the grain size and mineral composition of rivers, estuaries, and coasts.

2. Materials and methods

In June 2024, 45 samples of surface sediments were collected (Fig. 1). The sediment samples were obtained using a Petersen grab. Samples measuring 0-10 cm were collected, mixed, and stored in plastic bags in an ice box at 4°C until they were transported to the laboratory. In the laboratory, the samples were dried under air conditioning at 16°C and divided into two parts: one for grain size analysis and one for mineral analysis.

Fig. 1. Sampling sites in the Red river estuaries and coastal areas.

Grain size analysis was conducted at the Institute of Marine Environment and Resources after removing organic matter and salt with H_2O_2 (10%) and distilled water. The sediment was then wet sieved through a 63 µm sieve. The fraction >63 µm, remaining after the water had evaporated over a warm bath, was dried overnight at 105°C, and the particles between 2000 µm and 50 µm were sieved. For the <63 µm fraction, the water was decanted, and the particles were separated, filtered through filter paper under vacuum, and dried overnight at 105°C. The <63 µm fraction (5 g) was added to 10 ml of distilled water, combined with 1 ml of 10% NaOH, placed in an ultrasonic bath for 10 minutes to separate the particles, diluted to 1000 ml, and analysed via the pipette method [21]. The number of particles was calculated as a percentage of each grade. The sediment parameters, including the mean diameter (Md), were calculated from Eq. (1); sorting (S_0) from Eq. (2); and skewness (S_k) from Eq. (3), according to R.L. Folk, et al. (1957) [22]. GRADISTAT software (Kenneth Pye Associates Ltd., UK) was used to calculate the sediment parameters [23]. For quality control, three replicate samples were used, revealing that the standard deviations of Md, S_0, and S_k were less than 10%.

$$Md = \exp \frac{\ln P16 + \ln P50 + \ln P84}{3} \quad (1)$$

$$S_0 = \exp\left(\frac{\ln P16 - \ln P84}{4} + \frac{\ln P5 - \ln P95}{6.6}\right) \quad (2)$$

$$S_k = \frac{\ln P16 + \ln P84 - 2(\ln P50)}{2(\ln P84 - \ln P16)} + \frac{\ln P5 + \ln P95 - 2(\ln P50)}{2(\ln P25 - \ln P5)} \quad (3)$$

where *P5*, *P16*, *P25*, *P50*, *P84* and *P95* are the grain diameters at 5, 16, 25, 50, 84, and 95% cumulative percentile values, respectively.

Mineral composition analysis involved crushing and sieving the sample to a particle size of 0.074 mm. Approximately 2 g was then placed in a sample holder and gently pressed with a 4.5×5 cm glass plate to achieve a flat surface consistent with the height of the sample holder. The investigation was carried out on an XRD instrument (D8 Advance) utilising Cu($K_{\alpha 1,2}$) radiation. The optimum settings consisted of a 35 kV voltage, a 35 mA current, a step size of 2θ=0.015°, a scan step time of 3 s, and a measured interval of 2θ=5 to 65° (Fig. 2).

Diffraction data were recorded by a fully computerised system via the XRD COMMANDER® BRUKER program. The data were subsequently processed using Diffrac plus Evaluation® software [24]. The percentages of the different mineral phases were calculated via XRD using Eqs. (4) and (6).

The proportion of each mineral is calculated according to Eq. (4):

$$X_i' = \frac{J_{ij}}{K_{is}} \quad (4)$$

where X'_i is the content of phase *i* in the sample (%), J_{ij} is the j^{th} peak intensity of mineral *I*, and K_{is} is the coefficient for each mineral in the sample, which is given by Eq. (5):

$$K_{is} = \frac{X_i}{X_S} \cdot \frac{J_S}{J_i} \quad (5)$$

where $\frac{X_i}{X_S}$ is the content ratio of a single mineral to a standard sample in the mixed sample, J_S is the peak intensity of the standard sample, and J_i is the characteristic intensity of the sample to be determined.

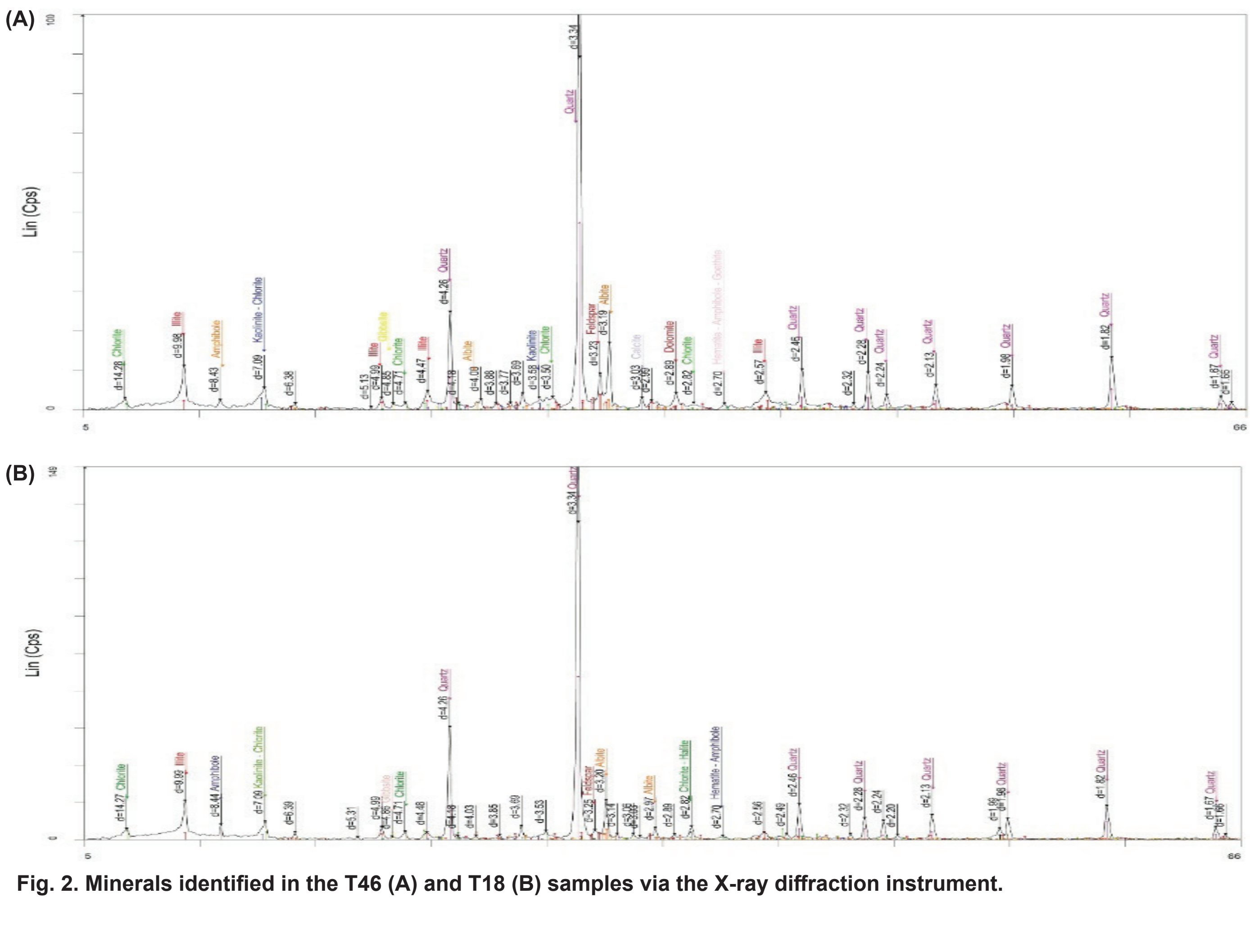

Fig. 2. Minerals identified in the T46 (A) and T18 (B) samples via the X-ray diffraction instrument.

The mineral content in the sample was calculated according to Eq. (6):

$$X_i = \frac{X'_i}{\sum_{i=1}^{n} X'_i} x100\% \quad (6)$$

where n is the number of mineral phases in the sample and $\sum_{i=1}^{n} X'_i = 100\%$.

This analysis was conducted at the Geological Analysis and Verification Center, Department of Geology, which is part of the Vietnam Ministry of Natural Resources and Environment.

Statistical analysis: Correlation analysis, cluster analysis, and factor analysis were employed. There were 45 samples, and 12 parameters were used. Pearson correlation analysis was utilised to determine the source of the sediments and the relationships between minerals and dynamic conditions. Cluster analysis revealed that similar samples were assigned to the same group, with each group distinguished by its characteristics. The factor analysis aimed to evaluate the influence of individual factors on the sedimentary environment in estuaries. The data were analysed using Origin Pro 2021 software.

3. Results

3.1. Grain size distribution

There were five different types of sediments: fine sand, very fine sand, very coarse silt, coarse silt, and medium silt (Table 1, Fig. 3).

Fine sand was found in coastal and estuarine areas (Table 1, Fig. 3). The Md value ranged from 128.73 to 222.35 µm, the sorting was well to moderately well sorted (S_0=1.28-1.49), and the skewness was fine to symmetrical (S_k from -0.26 to -0.06) (Table 1).

Very fine sand occurred in rivers, estuaries, and coastal areas from the Thai Binh estuary to the Day estuary (Fig. 3). Its Md ranged from 64.85 to 124.78 µm, its sorting ranged from well to very poor (S_0=1.34-4.46), and its skewness ranged from very fine to coarse (S_k from -0.77 to -0.13) (Table 1).

Very coarse silt was present in rivers, estuaries, and coastal areas from Tra Ly to Day estuaries (Fig. 3). The Md value was between 31.26 and 44.08 µm, the sorting was poorly to very poorly sorted (S_0=3.60-5.40), and the skewness was very fine to fine (S_k from -0.66 to -0.12) (Table 1).

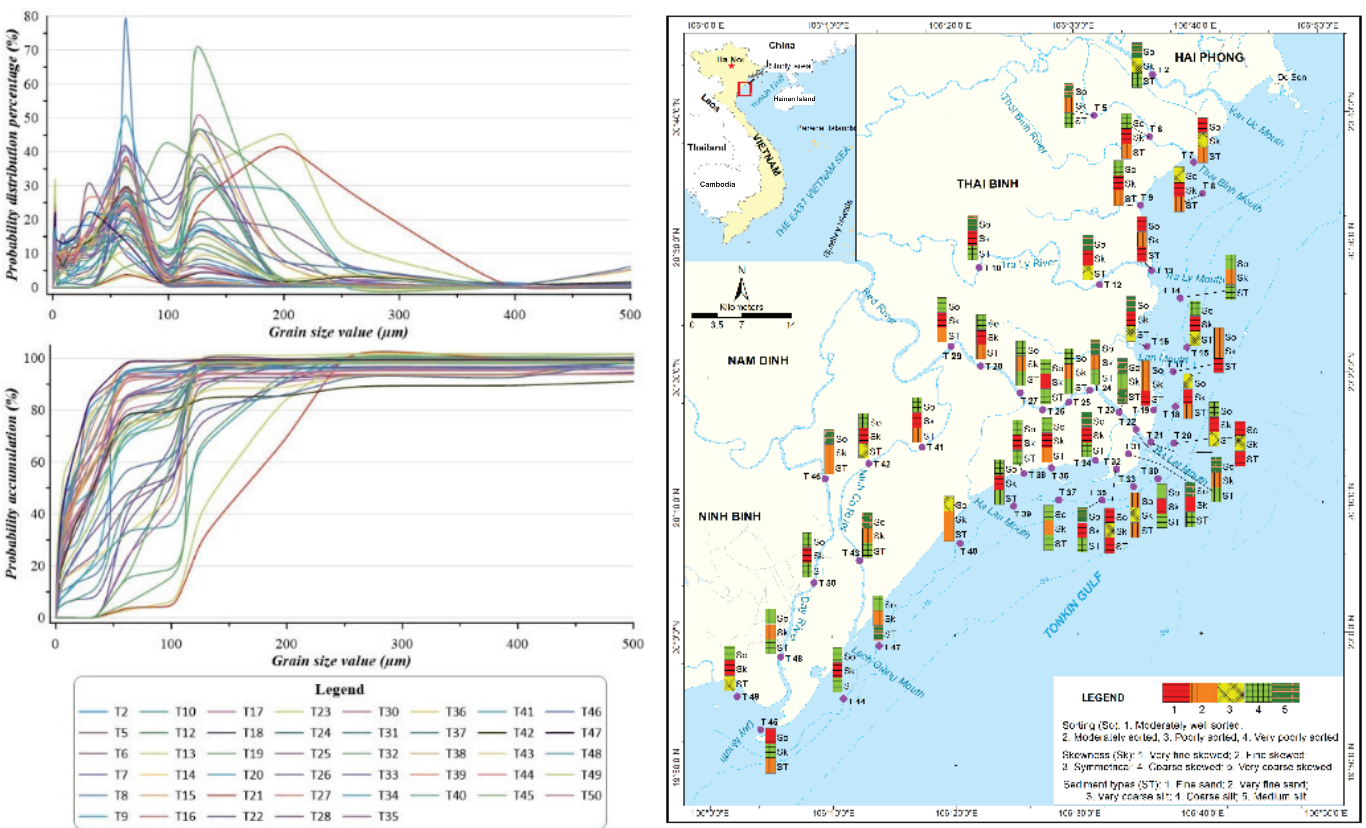

Fig. 3. Distribution of grain size, sediment types, S_0, and S_k in Red river estuaries and coastal areas.

Table 1. The values of Md, S_0, and S_k and the mineral content (%) of the surface sediments (Min-Max; mean ± standard deviation).

Sediment type	Fine sand (n=5)	Very fine sand (n=12)	Very coarse silt (n=8)	Coarse silt (n=16)	Medium silt (n=4)	Average
Mean diameter (Md) (μm)	128.73-222.35; 172.85±36.63	64.85-124.78; 93.09±22.19	31.26-44.08; 34.30±4.20	16.00-30.97; 23.50±5.12	14.91-15.39; 15.15±0.34	61.42
Sorting (S_0)	1.28-1.49; 1.40±0.08	1.34-4.46; 2.61±1.05	3.60-5.45; 4.35±0.69	3.63-4.89; 4.08±0.39	3.57-4.79; 4.18±0.86	3.42
Skewness (S_k)	-0.26÷-0.06; -0.16±0.09	-0.77-0.13; -0.37±0.28	-0.66÷-0.12; -0.50±0.17	-0.69÷-0.13; -0.38±0.18	-0.10-0.21; 0.06±0.22	-0.34
Illite	11.0-22.0; 14.8±4.3	12.0-23.0; 16.1±2.9	16.0-23.0; 19.6±2.4	15.0-27.0; 19.6±3.4	20.0-25.0; 22.7±2.5	18.3
Kaolinite	5.0-15.0; 7.8±4.1	5.0-15.0; 9.0±3.8	12.0-15.0; 13.5±1.1	10.0-16.0; 13.4±1.7	15.0-16.0; 15.7±0.6	11.8
Chlorite	6.0-7.0; 6.4±0.5	6.0-7.0; 6.1±0.3	6.0-7.0; 6.5±0.5	6.0-7.0; 6.5±0.5	6.0-7.0; 6.7±0.6	6.4
Quartz	43.0-59.0; 52.2±6.8	39.0-58.0; 50.4±6.2	41.0-48.0; 43.8±2.1	34.0-55.0; 42.9±4.9	38.0-44.0; 40.0±3.5	46
Feldspar	4.0-18.0; 8.4±6.4	3.0-15.0; 7.3±4.0	3.0-10.0; 5.0±2.4	3.0-12.0; 5.4±2.6	3.0-4.0; 3.3±0.6	6
Goethite	3.0-4.0; 3.8±0.4;	3.0-5.0; 3.9±0.5	4.0-5.0; 4.5±0.5	4.0-7.0; 4.8±0.7	4.0-5.0; 4.3±0.6	4.4
Gibbsite	1.0-3.0; 1.8±1.0	1.0-2.0; 1.4±0.4	1.0-2.0; 1.6±0.5	1.0-5.0; 1.8±0.9	1.0-2.0; 1.5±0.7	1.7
Calcite	1.0-1.0; 1.0±0.0	1.0-5.0; 1.9±1.3	1.0-4.0; 1.8±1.2	1.0-6.0; 2.3±1.3	1.0-2.0; 1.3±0.6	1.9
Amphibole	1.0-2.0; 1.5±0.5	1.0-3.0; 1.6±0.6	1.0-2.0; 1.5±0.4	1.0-2.0; 1.2±0.4	1.0-1.0; 1.0±0.0	1.4
Positions	Estuaries (T13, T21), coastal (T17, T19, T32)	Rivers (T6, T28, T41, T46), estuaries (T7, T9), coastal (T8, T18, T33, T36, T40, T45)	Rivers (T12, T42, T43), estuaries (T16), coastal (T15, T20, T34, T49)	Rivers (T5, T10, T24, T26, T27, T48, T50), estuaries (T22), coastal (T14, T30, T31, T35, T37, T38, T39, T44)	River (T2, T23, T25), coastal (T47)	

Coarse silt was deposited from Day to the Thai Binh estuaries, rivers, estuaries, and coastal areas (Fig. 3). The Md value ranged from 16.00 to 30.97 μm, the sorting was poorly to very poorly sorted (S_0=3.63-4.89), and the skewness was very fine to fine skewed (S_k from -0.69 to -0.13) (Table 1).

Medium silt was present in the river and coastal areas (Fig. 3), and the Md was between 14.91 and 15.39 μm. Sorting ranged from poor to very poor (S_0=3.57-4.79), and skewness was coarse to symmetrically skewed (S_k from -0.10 to 0.21) (Table 1).

Fine sand and very fine sand that were well sorted to moderately well sorted were commonly found in estuaries and coastal areas, where marine influence is more pronounced. The fine and very fine sands that were moderately sorted to poorly sorted were in rivers or coastal areas, where marine influence is less pronounced, near mangroves or behind sand bars; the skewness ranged from very fine, fine to symmetrically skewed. The coarse silt, very coarse silt, and medium silt were often poorly sorted to very poorly sorted, and the skewness was fine and very fine skewed, often distributed in rivers, estuaries, and coastal areas but at greater depths where the effects of marine or river dynamics are weak. Both coarse and fine sediments with skewness were fine to very finely skewed; this suggests that fluvial processes dominate over marine processes.

3.2. Mineral composition distribution

The mineral composition of the sediments consists of nine common minerals: quartz, illite, kaolinite, chlorite, feldspar, goethite, calcite, gibbsite, and amphibole (Fig. 4).

Quartz had the highest content, ranging from 34.0 to 59.0%, with an average of 46.0% (Table 1). The high quartz contents were found in fine sand and very fine sand and were distributed along coastal, estuarine, and river areas (Table 1, Fig. 4).

Illite was the second most abundant mineral, ranging from 11.0 to 27.0%, with an average of 18.3%. The high content was in medium silt, coarse silt, and very coarse silt, distributed in rivers, coastal, and estuarine areas (Table 1, Fig. 4). The kaolinite content ranged from 5.0 to 16.0%, with an average of 11.8%. High contents were found in medium silt, coarse silt, and very coarse silt, distributed in rivers, estuaries, and coastal areas (Fig. 4).

The chlorite content slightly fluctuated between 6.0 and 7.0%, with an average of 6.4%. High contents were present in medium silt, coarse silt, and very coarse silt, distributed in rivers, coastal, and estuarine areas (Table 1, Fig. 4). The feldspar content varied between 3.0 and 18.0%, with an average of 6.0%. High content was found in fine sand and very fine sand, distributed in coastal, estuarine, and river areas (Table 1, Fig. 4).

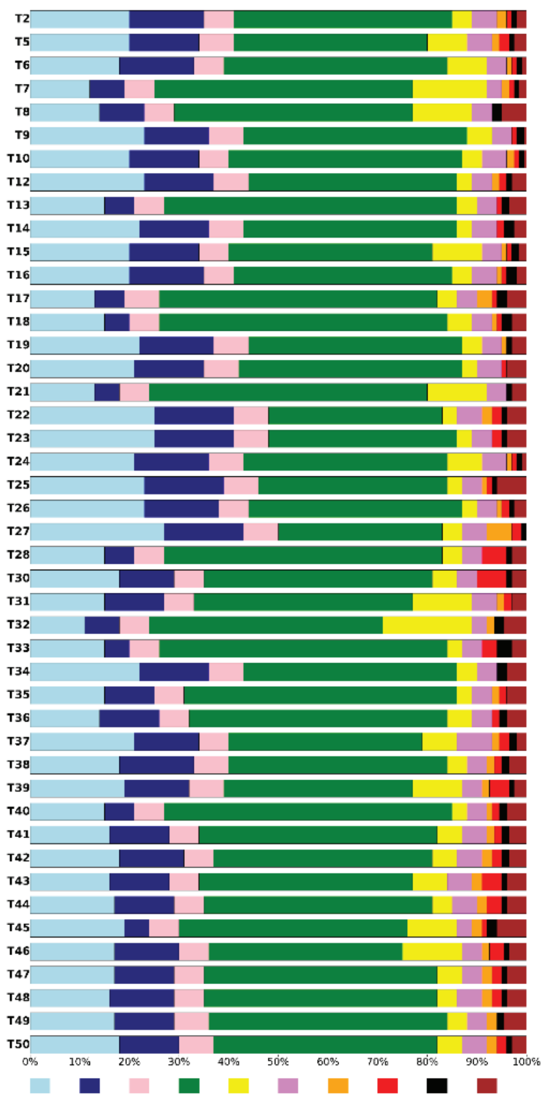

Fig. 4. Distribution of minerals in the Red river estuaries and coastal areas.

The goethite content was between 3.0 and 7.0%, with an average of 4.4%. High contents were found in very coarse silt, coarse silt, and medium silt, distributed in rivers, estuaries, and coastal areas (Table 1, Fig. 4). The gibbsite content varied between 1 and 5%, with an average of 1.7%. High content was found in fine sand and coarse silt, distributed across rivers, estuaries, and coastal areas (Table 1, Fig. 4).

The calcite content was between 1 and 6%, with an average of 1.9%. High contents were found in coarse silt, distributed in rivers, coastal, and estuarine areas (Table 1, Fig. 4).

Amphibole was the least abundant mineral, ranging from 1.0 to 3.0%, with an average of 1.4%. High contents were found in fine sand, very fine sand, and very coarse silt, distributed in coastal, river, and estuary areas (Fig. 4).

3.3. Correlations between sediment parameters

As shown in Fig. 4, the correlations between grain size and mineral parameters were both positive and negative. These correlations varied from weak ($0.25<R\leq0.5$) to moderate ($0.5<R\leq0.75$) and strong ($0.75<R\leq1$). There were positive correlations between illite, kaolinite, and chlorite; between goethite and sorting (S_0); between goethite and illite and kaolinite; between Md and quartz, feldspar, and amphibole; and between calcite and S_0 (Fig. 5).

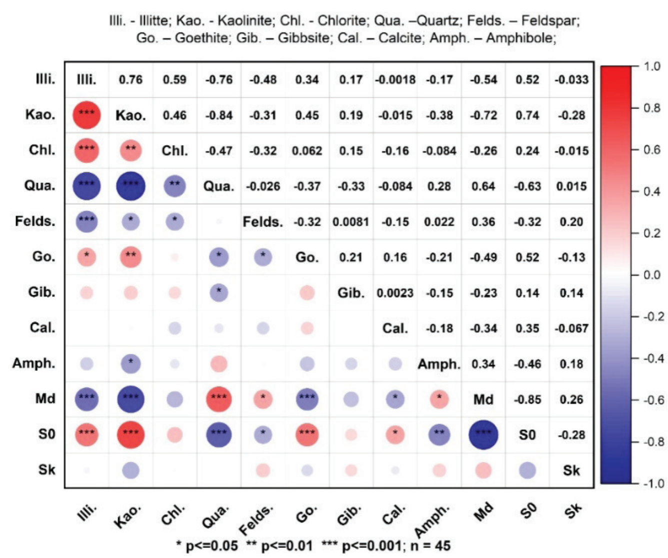

Fig. 5. Pearson correlation coefficient matrix between minerals and grain sizes.

There were negative correlations between quartz, feldspar, Md, amphibole and illite, kaolinite, and chlorite; between goethite and quartz; feldspar and Md; between gibbsite and quartz; between S_0 and Md; and between calcite and Md (Fig. 5).

Negative correlations among minerals or between grain sizes and minerals signify adverse environmental conditions for mineral formation. Positive correlations among minerals such as illite, kaolinite, and chlorite suggest a common source

Table 2. Comparative grain sizes and compositions of minerals in several areas of Vietnam.

Coastal area		Red river estuaries	Ba Lat-Thai Binh estuaries (core sediments)	Van Uc-Lach Tray estuaries (core sediments)	Day estuary (core sediments)	Ha Long bay	Cat Ba bay	Gulf of Tonkin
Grain size parameters	*Md (µm)*	61.4	44	18	57	59.2	299	75
	S_0	3.4	2.8	2.5	2.2	6.1	2.8	3.7
	S_k	-0.3	-	-	-	-0.2	-0.2	-0.2
Mineral composition (%)	*Illite*	18.3	23.1	24	19.7	15	18	14.3
	Kaolinite	11.8	11.3	19.5	9.1	15	14	10
	Chlorite	6.4	7.4	8.7	7	6	5	5
	Quartz	46	39.3	28.5	46.3	49	26	50.5
	Feldspar	6	6.7	5.6	7.2	4	2	6.9
	Goethite	4.4	5.7	6.6	5.1	5	4	4.7
	Gibbsite	1.7	-	-	-	-	-	-
	Calcite	1.9	-	-	-	6	10	2.7
	Amphibole	1.4	-	-	-	-	-	-
References		This study	[12]			[26]	[27]	[28]

of sediment; positive correlations between minerals and Md indicate a strong dynamic sedimentary environment, such as Md, quartz, feldspar, and amphibole; and positive correlations between illite and kaolinite, S_0, and goethite indicate a weak dynamic environment.

In the Red river estuaries, kaolinite, illite, quartz, feldspar, calcite, and amphibole had significant correlations with Md and S_0, whereas chlorite and gibbsite had insignificant correlations. Fine sediment is widely distributed in estuaries, where it adsorbs organic matter from water; chlorite adsorbs organic matter with a size >16 µm [15], and the gibbsite is adsorbed, creating colloidal systems [17] that lead to increased size and mass balance with other minerals and Md; as a result, gibbsite and chlorite have insignificant correlations with other parameters.

4. Discussion

4.1. Comparison of grain sizes and mineral compositions with other areas in Vietnam

The sediments in the estuaries of the Red river are readily supplied by rivers and are finer than those in Cat Ba bay and the Gulf of Tonkin but coarser than the sediments in Ha Long bay (Table 2).

Comparison with previous studies of the estuaries of the Red river system, particularly the Lach Tray-Van Uc, Thai Binh-Ba Lat, and Day estuaries [12], revealed that the contents of illite, chlorite, and goethite were lower than those in the Ba Lat-Thai Binh and Van Uc-Lach Tray estuaries, whereas the quartz content was greater [12]. Compared with those in the Day estuary, the contents of illite, chlorite, quartz, feldspar, and goethite were higher than those in this study, except for kaolinite [12]. At Van Uc-Lach Tray, the Ba Lat-Thai Binh estuaries had greater tidal influence than the Day estuary. Moreover, the wave influence is more pronounced on the Day estuary [25], indicating that the S_0 value of sediments on the Day estuary is lower than that at Ba Lat, Van Uc, and Lach Tray estuaries. This study included rivers, estuaries, and coastal areas, with rivers less affected by tides and waves; therefore, the S_0 value of sediments is greater than that reported in previous studies focused primarily on the intertidal zone. This confirmed that the Red river contained significant amounts of illite, kaolinite, and quartz, which are predominantly transported to the coast via rivers.

In Ha Long Bay, the contents of kaolinite, quartz, goethite, and calcite were higher than those in this study, whereas the contents of illite, chlorite, and feldspar were lower (Table 2) [26]. Ha Long bay also receives sediment from the Red river system and surrounding areas through erosion sources [13]. In Ha Long bay, the dynamic regime was weaker than that in the Red river estuaries, characterised by smaller Md and S_0 high values.

In Cat Ba Bay, the contents of kaolinite and calcite were higher than those in this study, whereas the contents of illite, chlorite, quartz, feldspar, and goethite were lower (Table 2). Kaolinite was sourced via erosion or supplied from rivers of the Thai Binh system, whereas calcite received biological deposits [27]. Sediments are distributed mainly near coral reefs, which are characterised by a stronger environment than the Red river estuary, characterised by Md and a lower S_0.

The Gulf of Tonkin is influenced by several river drainages, and the contents of illite, kaolinite, chlorite, and goethite are lower than those in this study. However, the contents of quartz, feldspar, and calcite were higher than those in this study (Table 2) [28]. The Gulf of Tonkin has a stronger environment than the Red river estuary and is characterised by high Md and high quartz contents.

4.2. Sediment groups and environmental characteristics

There were 45 samples and 12 parameters analysed in the cluster. The samples were divided into two groups: Group 1, with 34 samples, and Group 2, with 11 samples. The parameters were classified into two groups: Group 1 (7 parameters) and Group 2 (5 parameters) (Fig. 6).

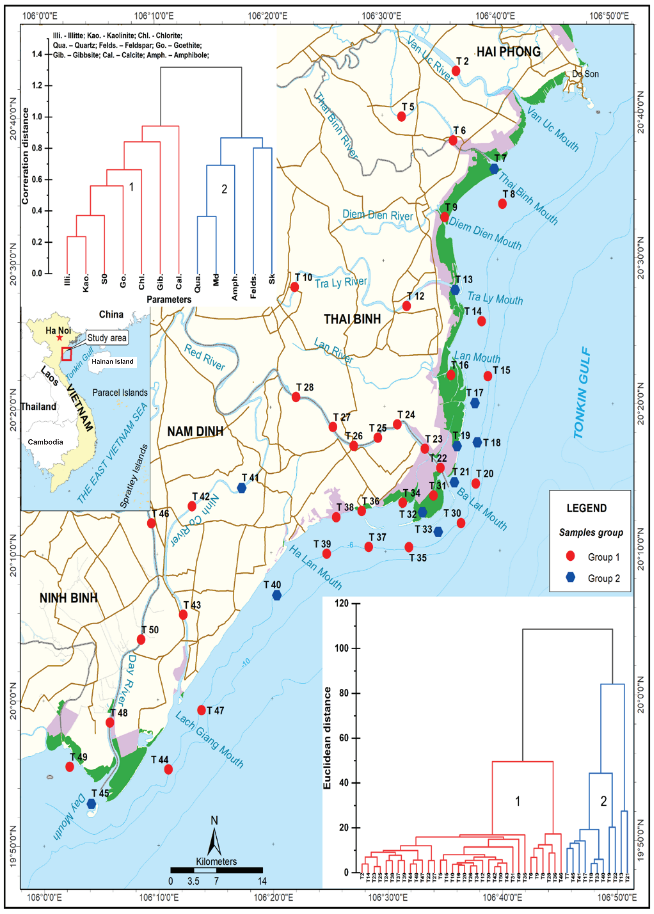

Fig. 6. Groups of samples and parameters in the Red river estuaries and coastal areas.

Table 3. Average of the parameters in the sediment groups.

Parameters	Group 1	Group 2
Number of stations	34	11
Illite (%)	19.35	15.09
Kaolinite (%)	13.24	7.18
Chlorite (%)	6.44	6.18
Quartz (%)	43.76	52.82
Feldspar (%)	5.50	7.55
Goethite (%)	4.53	3.82
Gibbsite (%)	1.25	1.14
Calcite (%)	1.84	1.00
Amphibole (%)	1.13	1.68
Md (µm)	34.20	141.45
S_0	4.00	1.63
S_k	-0.39	-0.18

Md (µm): Mean diameter; S_0: Sorting coefficient; S_k: Skewness.

The sample groups were split into two groups: Group 1 was distributed in river, coastal, and estuarine areas from Van Uc to Day (Fig. 6). Group 1 was composed of very coarse silt (Md=34.20 µm) with very poor sorting (S_0=4.00) and had higher contents of illite, kaolinite, and chlorite than Group 2, whereas the contents of quartz, feldspar, and amphibole were the lowest (Table 3). Group 2 was fine sand (Md=141.45 µm) and moderately sorted (S_0=1.63), distributed in coastal estuaries and inside rivers from Thai Binh to Ninh Co, and contained illite, kaolinite, and chlorite; quartz, feldspar, and amphibole had higher values than Group 1 (Table 3).

The parameter groups were split into two groups: Group 1 included illite, kaolinite, S_0, goethite, chlorite, gibbsite, and calcite. Group 2 included quartz, Md, amphibole, feldspar, and S_k (Fig. 5). The parameters Md, S_0, and Sk are used to evaluate sedimentary environmental dynamics. The weak dynamic was Group 1, and the strong dynamic was Group 2.

The mean diameter (Md) and quartz content are strong dynamic environmental indicators. The sorting (S_0) and clay mineral contents are weak dynamic indicators. This was shown by the positive correlation between them. The distributions of the two sample groups are shown in terms of the dynamic conditions at different locations. Group 1 has the most samples and has weaker environmental dynamics than Group 2. The Md value and quartz content are lower than those of Group 2, which are distributed in rivers, estuaries, and coastal areas and are influenced more by rivers than coasts; thus, the sorting is poor, and the content of clay minerals is high. Group 2 is distributed in estuaries and coastal areas and is more affected by waves and currents in coastal areas, so the Md value and content of quartz are high, the sorting value is lower than that of Group 1, and the clay mineral content is low.

4.3. Factors affecting sedimentary environments and sediment sources

Factor analysis revealed four major components, with proportions of 40.7% for factor 1 (FA1), 13.0% for factor 2 (FA2), 10.7% for factor 3 (FA3), and 8.6% for factor 4 (FA4) (Table 4). FA1 was influenced by illite, kaolinite, chlorite, quartz, goethite, Md, and S_0. FA2 was affected by chlorite and calcite. FA3 was influenced by feldspar and gibbsite. S_k impacted FA4.

Table 4. Results of factor analysis between minerals and grain size parameters.

N^0	Parameters	FA1	FA2	FA3	FA4
1	Illite	0.82	0.35	-0.21	0.09
2	Kaolinite	0.91	0.13	-0.04	-0.23
3	Chlorite	0.51	0.55	-0.31	-0.03
4	Quartz	-0.82	-0.32	-0.28	0.13
5	Feldspar	-0.44	0.14	0.67	-0.44
6	Goethite	0.59	-0.22	0.06	0.29
7	Gibbsite	0.29	0.28	0.55	0.30
8	Calcite	0.22	-0.64	0.20	0.41
9	Amphibole	-0.45	0.28	-0.35	0.38
10	Md	-0.86	0.23	-0.06	-0.06
11	S_0	0.87	-0.29	0.07	-0.05
12	S_k	-0.26	0.49	0.37	0.52
	Variance	4.9	1.6	1.3	1.0
	Percentage of variance (%)	40.7	13.0	10.7	8.6

Four factors characterise the sources that supply minerals: continental sources are most common in Red river estuaries, and illite, kaolinite, quartz, chlorite, and goethite are significantly correlated. Additionally, the second source of chlorite is the product of metamorphic weathering and leaching from the soil in the basin of the Red river system, which is very common. When the water pH is ≥8.6, calcium carbonate precipitation begins, and this process is usually short-lived [29]. If calcite is formed from biological shells, it must be positively correlated with Md. The results of this study are negatively correlated with Md, indicating mechanical formation (Md) and calcite formation by chemicals. The third source provides feldspar and gibbsite, where gibbsite is a weathering product from clay minerals. Because the gibbsite content is low, they are both positively correlated with clay minerals but have little significance.

The distribution of minerals is influenced by hydrology and sediment supply. Through the source of total suspended solids via estuaries, the minerals derived from the erosion of the rocks and soils in the basin are mainly categorised as clay minerals, quartz, feldspar, and amphibole. Calcite, gibbsite, and goethite are also produced via chemical weathering and precipitation processes. However, the majority of the supply comes from erosion rather than chemical weathering and precipitation processes.

5. Conclusions

The Red river estuaries and coastal areas contained five sediment types: fine sand, very fine sand, very coarse silt, coarse silt, and medium silt, with very fine sand and coarse silt being common.

The fine sands were sorted from moderately well to well. The very fine sand ranged from very poorly to well sorted. The very coarse silt, coarse silt, and medium silt ranged from very poorly to poorly sorted. In the sediment, the contents of quartz, illite, kaolinite, chlorite, feldspar, goethite, calcite, gibbsite, and amphibole were 46.0, 18.3, 11.0, 6.4, 6.0, 4.4, 1.9, 1.7, and 1.4%, respectively.

Two groups were identified: the weak dynamic group, characterised by coarse silt distributed in rivers, estuaries, and coastal areas, with high contents of illite and kaolinite, whereas the quartz and feldspar contents were low. The strongly dynamic group was fine sand, distributed in coastal areas, estuaries, and rivers, characterised by high contents of quartz, feldspar, and amphibole.

The source minerals in sediment derived from the erosion of soils and rocks in catchments are common and rich in illite, kaolinite, chlorite, quartz, feldspar, and amphibole, whereas other sources, including precipitation such as calcite and weathering sources such as gibbsite and goethite, are poor.

CRediT author statement

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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