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Characteristic and distribution of grain sizes and minerals in sediments from the Vietnamese Gulf of Tonkin

Dang Hoai Nhon[1*], Nguyen Van Thao[1], Tran Duc Thanh[1], Nguyen Dac Ve[1], Bui Van Vuong[1], Lai Thi Bich Thuy[2], Bui Thi Thanh Loan[3], Hoang Thi Chien[1], Duong Thanh Nghi[1]

[1]Institute of Marine Environment and Resources, Vietnam Academy of Science and Technology, 246 Da Nang Street, Cau Tre Ward, Ngo Quyen District, Hai Phong City, Vietnam
[2]Center for Geological Experiment Analysis, Ministry of Natural Resources and Environment, Km9, Nguyen Trai Street, Van Quan Ward, Ha Dong District, Hanoi, Vietnam
[3]Institute of Environment, Vietnam Maritime University, 484 Lach Tray Street, Kenh Duong Ward, Le Chan District, Hai Phong City, Vietnam

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Abstract:

Grain sizes and minerals of sediments from the Gulf of Tonkin were evaluated from 30 surface samples and 50 samples from two cores. The distribution of grain sizes and minerals from these samples were determined to help understand sediment characteristics, origins, and environmental dynamics. There were five sediment types: fine and very fine sands, very coarse, coarse, and medium silts. Minerals in the sediment were identified as decreasing in terms of the content of quartz, illite, kaolinite, chlorite, feldspar, goethite, halite, calcite, gibbsite, aragonite, and montmorillonite. Contents of major minerals such as quartz, illite, kaolinite, and chlorite varied from nearshore to offshore; quartz was higher nearshore than offshore; illite, kaolinite, and chlorite from nearshore were lower than offshore; calcite and aragonite were low nearshore and higher in the offshore; goethite was lower offshore and higher nearshore; and, finally, halite was high offshore and low nearshore. Surface sediments were divided into three groups based on sedimentary environment characteristics: Group 1 was distributed nearshore with strong dynamics, Group 2 in bays and nearshore with weak dynamics, and Group 3 was distributed offshore with quiet dynamics. The origin of the sediments was weathering and erosion from the mainland and islands under the river and sea processes in the Gulf of Tonkin with quartz, illite, kaolinite, feldspar, chlorite, and montmorillonite found present in the sediment. Geochemical processes produced goethite, gibbsite, halite, and pyrite in the sediments while biological substances produced calcite and aragonite.

Keywords: **grain size, Gulf of Tonkin, minerals, Vietnam.**

Classification numbers: **5.1, 5.3**

1. Introduction

The Gulf of Tonkin, shared by Vietnam and China, has contributed significant economic value such as fishing, minerals, and transportation for both countries. Therefore, understanding the environment's characteristics plays a key role in effective natural resource utilisation and supporting sustainable economic development. The distribution and provenance of clay minerals in the Gulf's surface sediments were studied, and four sedimentary sources have been identified, including southern mainland China, Hainan island, the Red river system, and the mouth of the Gulf of Tonkin [1]. The sediments are typically mud, occasionally sand, and poorly to very poorly sorted [2].

Ten sedimentary fields were distributed around the Co To islands (Vietnam), including sandy gravel, gravelly sand, sand, gravelly muddy sand, sand mixed gravel, muddy sand, gravelly mud mixed sand, muddy sand, muddy sandy gravel, and sandy mud. The sediments contained quartz in the form of minerals, detritus, feldspar, mica, and shells. The origins of these surface sediments were mainly continental [3].

On the western coast of the Gulf of Tonkin, rocks, gravel, sand, and mud were present. Rocks and gravel were often found near the rocky coast, while sand and mud were widespread in the intertidal zone, beaches, and estuaries [4]. Sand and silt were also common in the intertidal zone at the mouth of the Red river system [5, 4] and Ha Long bay [6]. The sediment sources of the Red river system and partially eroded and weathered sources of the islands and surrounding geological system have been identified based on smectite in Ha Long bay sediments [7].

Around the Cat Ba islands, eight sediment types were distributed, decreasing coarse silt > very coarse silt > medium sand, very fine sand > very coarse sand, fine > coarse sand, and very fine gravel. The mineral content of sediments decreased with concentration: quartz > illite > aragonite > kaolinite > calcite > chlorite > goethite > halite > feldspar and less montmorillonite and dolomite. Calcite, aragonite, goethite, and halite from marine organisms were formed by chemical processes, while quartz, illite, kaolinite, chlorite, and montmorillonite from terrigenous sources were formed by weathering and erosion [8].

Previous studies on grain size and mineralogy have been conducted in the Gulf of Tonkin, both in Vietnam and China. However, most surveys conducted on the Vietnamese side were

*Corresponding author: Email: nhondh@imer.vast.vn

about the nearshore and poorly conducted offshore. This study provides further information on offshore grain size and mineral composition to better understand the Gulf of Tonkin's sedimentary environment.

2. Materials and methods

The Gulf of Tonkin covers an area of 126,250 km^2, and its border between Vietnam and China was established in 2000 and took effect in 2004. The Vietnamese side has large river systems such as the Red river, the Ca river, and the Ma river, which meet the Gulf. In addition, several smaller rivers in Quang Ninh province also meet the Gulf. Along the coast, there are ports such as Hai Phong, Nghi Son, and Cua Ong in Vietnam, and Fangcheng in China. The Gulf of Tonkin is influenced by the northeast (NE) monsoon from November to March and by the southwest (SW) monsoon from May to September, which reverses the direction of the current. Near the coast, it flows from NE to SW during NE monsoon and from SW to NE during SW monsoon. In the offshore area, the current is stable from NE and SW during monsoons. Tidal levels in the Gulf of Tonkin vary from north to south, with the highest at Mong Cai (4.7 m) and the lowest at Quang Tri (1.16 m) during spring tides [9].

In July 2018, the Petersen grab collected thirty surface samples to understand the sediment characteristics of the bay, and two sediment cores were hand-cored in the estuary and lagoon to understand changes in the sediment environment in the coastal waterbody (Fig. 1). Surface samples were collected from 0-10 cm from the beach to a depth of 50 m. The C1 core was collected from

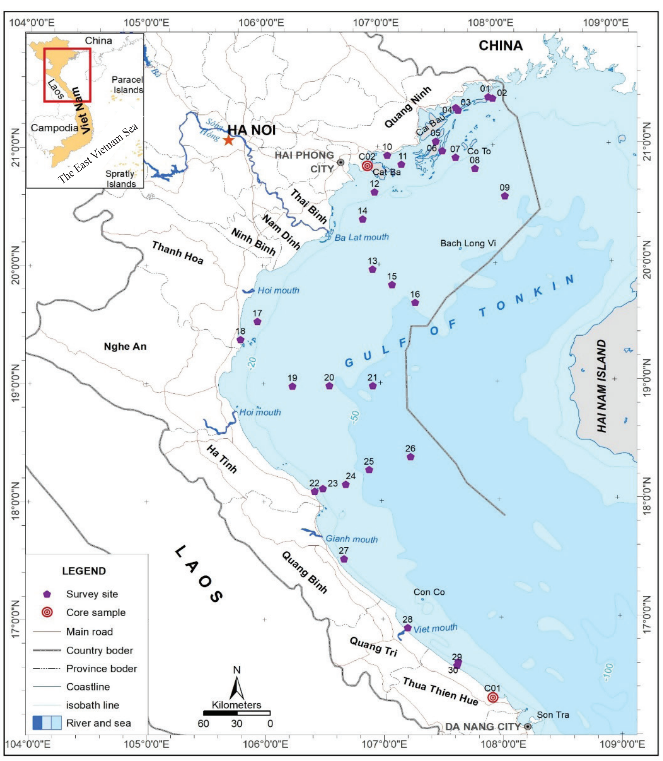

Fig. 1. Sample positions in Gulf of Tonkin.

Tam Giang - Cau Hai lagoon, and the C2 core was collected from Bach Dang estuary. Each 70-cm-long sediment core was cut into sections: 2 cm from 0 to 20 cm, 3 cm from 20 to 50 cm, and 4 cm from 50 cm to the end. The samples were stored at 4^{o}C on the way to the laboratory. At the laboratory, the samples were dried under room conditions for grain size and mineral analysis.

Grain size analysis: The sediments were salt-washed with distilled water to remove organic matter by H_2O_2, then wet sieved through a 63-µm sieve. The >63 µm fraction left after sieving was evaporated over a warm bath and dried overnight at 105^{o}C, and the particles were sieved between 2000 and 50 µm. For the <63 µm fraction, once all particles had deposited, the water was decanted and filtered through filter paper in a vacuum and dried overnight at 105^{o}C. The <63 µm fraction (5 g) was added to 1 ml 10% NaOH, placed in an ultrasonic bath for 10 min for particles to separate, diluted with distilled water to 1000 ml, then analysed by the pipette method [10]. Sediment parameters were calculated using the GRADISTAT software, and sediment types were classified according to a previous study [11]. This analysis was carried out at the Institute of Marine Environment and Resources, Vietnam Academy of Science and Technology.

Mineral composition analysis: The samples were crushed and sieved with a 0.07 mm sieve. About 2 g of each sample was placed in the sample hole, and the sample was pressed on a 4.5x5 cm glass plate to form a smooth surface. The samples were analysed on a D8 Advance with Cu-$K_{\alpha1,2}$ radiation, 35 kV voltage, and 35 mA current with 2Θ steps=0.015^o, a 3-sec dwell time and 2Θ range of 5-60^o. This analysis was conducted at the Center for Geological Experimental Analysis of the Ministry of Natural Resources and Environment, Vietnam.

Statistical analysis: Pearson correlation coefficients, clustering, and factor analysis (FA) were used. Correlation coefficients were used to identify the sources of minerals (quartz, illite, kaolinite, chlorite, feldspar, goethite, halite, calcite, aragonite, gibbsite, and montmorillonite) and the conditions of environmental dynamics between grain size parameters (Md, S_0, S_k). Clustering was used to group sedimentary data based on similarity in sediment parameters and to determine the origin, sediment supply, and dynamic conditions of each group. FA was used to estimate which parameters influence sedimentary environments, determine the origin and relationship of minerals, and identify supplies and parameters that strongly control the environment. All these techniques were performed using Origin Pro 2021 software (OriginLab Corporation).

3. Results

3.1. Distribution of sediment types

Five types of sediment were found in the Gulf of Tonkin. The surface sediments included fine sand, very fine sand, very coarse silt, coarse silt, and medium silt. The sediment cores were divided into three types, which were very coarse silt, coarse silt, medium silt. There were no fine or very fine sands.

Fine sand was only found in surface sediments distributed nearshore at depths of up to 30 m from the coast (samples 1, 2, 6, 22, 27), with only one offshore sample (sample 24). Fine sand accounted for 20% of the samples (5/30) (Fig. 2). The mean diameter (Md) was 0.130-0.244 mm, sorting (S_0) was moderately well to poorly sorted (S_0=1.45-3.81), and skewness (S_k) was symmetrical to very coarse skewed (S_k=0.05-0.34).

Very fine sands were only found in surface sediments and were absent in cores. They were distributed from nearshore (samples 4, 11, 17, 28) to offshore (samples 8, 13, 15, 19, 20, 21), accounting for 33.3% of the samples (10/30) (Fig. 2). Md was 0.063-0.112 mm, S_0 was moderately well to very poorly sorted (S_0=1.78-1.53), and S_k was very fine to coarse skewed (S_k=-0.52-0.16).

Very coarse silt was present in both surface and core sediments. Surface sediment was distributed nearshore (samples 7, 10, 12, 14) and offshore (samples 16, 25), accounting for 20% of the samples (6/30 samples) (Fig. 2). The Md varied from 0.032 to 0.061 mm, S_0 was poorly sorted (S_0=2.47-3.92), and S_k was very fine skewed (S_k ranging from -0.61 to -0.38). In C1, very coarse silts were uniformly distributed from 0 to 70 cm, presenting in 100% of the samples (25/25). The Md varied from 0.038 to 0.054 mm, S_0 from 1.79 to 2.41, indicating moderately well to poorly sorted, and S_k ranged from 0.59 to -0.03, showing a very fine to symmetric skew. In C2, very coarse silt was distributed alternately from the top, middle, and bottom of the core, accounting for 60% of the samples (15/25). The Md was 0.031-0.047 mm, S_0 ranged from 2.25 to 2.52, indicating poorly sorted, and S_k ranged between -0.70 to 0.07 indicating very fine to symmetrical skew.

Coarse silt was found in surface and C2 core sediments, distributed nearshore (samples 3, 5, 18) and offshore (samples 9, 26), accounting for 16.6% of samples (5/30) (Fig. 2). The range of Md was 0.021 to 0.029 mm, S_0 was poorly to very poorly sorted (S_0=2.71-4.59), and S_k was very fine to fine skewed (S_k=-0.45 to -0.12). In C2, coarse silt ranging from 4 to 47 cm accounted for 36% of the samples (9/25), Md was from 0.021 to 0.030 mm, S_0 was poorly sorted (S_0=2.59-3.78), and S_k was very fine to symmetrically skewed (S_k=-0.62 to -0.03).

Surface and C2 core sediments contained medium silt. Surface sediments distributed nearshore (samples 13, 29, 30) accounted for 10% of the samples (3/30) (Fig. 2). The Md was 0.013 to 0.015 mm, S_0 was very poorly sorted (S_0=4.00-4.73), and S_k was symmetrical skewed (S_k varied from -0.10 to -0.09). In C2, only 4% of the total samples (1/25) had a length of 38-41 cm, S_0 indicating poorly sorted (S_0=3.06), and S_k showing coarse skewed (S_k=0.30).

3.2. Distribution of minerals in sediments

Various sedimentary minerals were identified including quartz, illite, kaolinite, chlorite, feldspar, goethite, halite, calcite, aragonite, gibbsite, and montmorillonite (Table 1).

Table 1. Contents of minerals in sediment.

Position	Levels	Minerals (%)											
		Mont.	*Illi.*	*Kao.*	*Clo.*	*Qua.*	*Fel.*	*Go.*	*Ha.*	*Py.*	*Gip.*	*Can.*	*Ara.*
Surface sediment (n=30)	Min.	0.0	3.0	3.0	2.0	26.0	3.0	3.0	0.0	0.0	0.0	0.0	0.0
	Max.	3.0	23.0	18.0	7.0	79.0	16.0	7.0	3.0	0.0	0.0	11.0	5.0
	Aver.	0.3	14.3	10.0	5.0	50.5	6.9	4.7	1.8	0.0	0.0	2.7	0.2
	SD.	0.8	5.0	4.7	1.3	13.5	3.7	0.8	0.8	0.0	0.0	3.1	0.9
C1 (n=25)	Min.	0.0	16.0	12.0	5.0	32.0	3.0	2.0	0.0	0.0	1.0	0.0	0.0
	Max.	0.0	25.0	19.0	7.0	48.0	7.0	4.0	2.0	4.0	3.0	3.0	7.0
	Aver.	0.0	19.6	15.0	5.4	41.3	4.8	3.2	0.8	2.6	2.0	0.4	0.4
	SD.	0.0	2.5	1.5	0.6	4.1	1.1	0.8	1.0	1.0	0.5	1.0	1.6
C2 (n=25)	Min.	0.0	17.0	6.0	5.0	35.0	3.0	3.0	0.0	2.0	0.0	0.0	0.0
	Max.	0.0	25.0	16.0	7.0	51.0	13.0	4.0	2.0	4.0	2.0	0.0	0.0
	Aver.	0.0	20.5	12.8	6.0	42.7	6.2	3.6	1.0	2.8	0.4	0.0	0.0
	SD.	0.0	2.1	2.1	0.5	3.7	2.5	0.5	1.0	0.7	0.8	0.0	0.0

Mont.: Montmorillonite; Illi.: Illite; Kao.: Kaolinite; Clo.: Chlorite; Qua.: Quartz; Fel.: Feldspar; Go.: Goethite; Hal.: Halite; Can.: Calcite; Ara.: Aragonite; Gip.: Gibbsite; Py.: Pyrite.

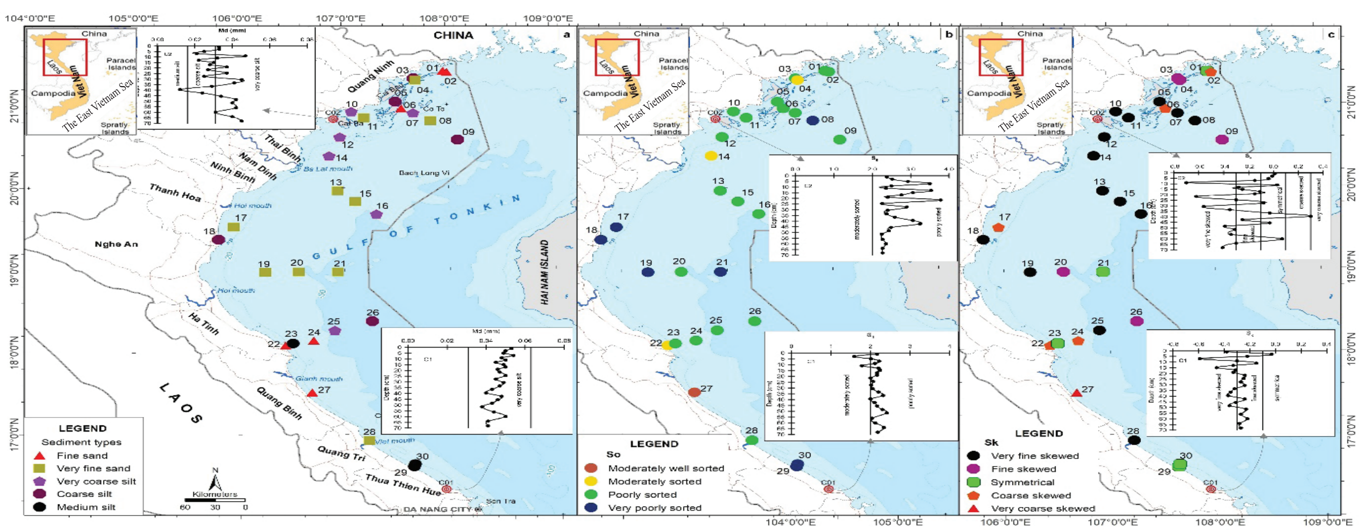

Fig. 2. Distribution of sediment types, sorting, and skewness.

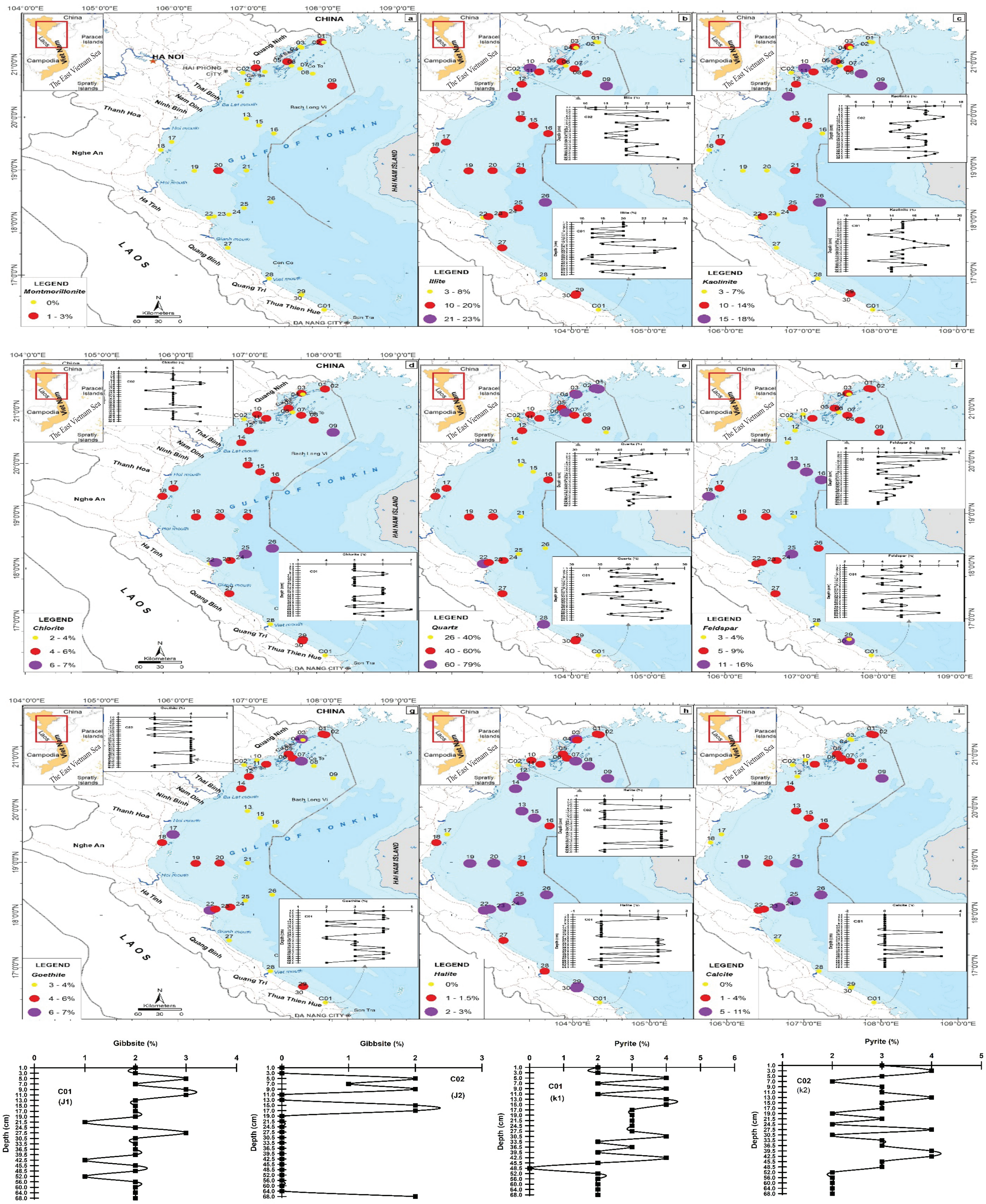

Fig. 3. Distribution of montmorillonite (A), illite (B), kaolinite (C), chlorite (D), quartz (E), feldspar (F), goethite (G), halite (H), calcite (I), gibbsite with (J1, J2) showing depth distribution (J), and pyrite with (K1, K2) showing depth distribution (K).

Montmorillonite was detected in surface sediments at concentrations ranging from 0 to 3%, with highest values of 1-3% found nearshore (samples 1, 5, 10) and offshore (samples 9, 20), but not in other areas. It did not appear in the cores (Fig. 3A).

Illite was found in both surface and core sediments. Surface sediment content ranged from 3 to 23% and averaged 14.3%, with the highest concentrations (21-23%) were found offshore (samples 9, 26) and nearshore (samples 10, 14), 10-20% concentrations were found nearshore (samples 3, 5, 7, 11, 12, 17, 18, 23, 27, 29, 30) and offshore (samples 8, 13, 15, 16, 19, 20, 21, 24, 25), and concentrations of 3-8% were found only nearshore (samples 1, 2, 4, 6, 22, 28). In C1, illite content ranged from 16 to 25% with an average of 19.6%. Illite contents ranging between 21-25% were found from the middle to the bottom core. Contents ranging between 18-20% were found in the top, middle, and bottom, while 16-17% contents were found in the top and middle. In C2, illite contents ranging between 21-25% was distributed in the top, middle, and bottom of the core, with contents of 18-20% distributed in the top, middle, and bottom of the core, and 17% content was found in the top of the core (Fig. 3B).

The kaolinite content in surface sediments ranged from 3 to 18% with an average of 10%. The offshore and nearshore content was 15-18% (samples 9, 8, 26) and (samples 10, 14), respectively. Kaolinite contents ranging between 10-14% were found nearshore (samples 3, 5, 7, 11, 12, 17, 23, 30) and offshore (samples 13, 15, 21, 25), and 3-7% contents were found nearshore (samples 1, 2, 4, 6, 18, 22, 27, 28, 29) and offshore (samples 16, 19, 20, 24). In C1, the content range of 17-19% was found distributed in the top, middle, and bottom of the core. Meanwhile, contents of 15-16% kaolinite were found in the top, middle, and bottom of the core, and contents of 12-14% were distributed in the top, middle, and bottom of the core. In C2, kaolinite content ranged from 6 to 16% and averaged 12.8%, with the higher average content of 15-16% distributed in the top and bottom of the core, the 10-14% content range found most often in the top, middle, and bottom, and the 6-11% content range found in the middle and bottom of the core (Fig. 3C).

The chloride content in surface sediments ranged from 2-7%, with an average of 5.0%. The highest chlorite concentration of 6-7% was found near the coast (samples 12, 23, 30) and in the offshore area (samples 9, 13, 21, 25, 26). A chlorite concentration of 5% was the most abundant and found near the coast (samples 2, 3, 5, 7, 10, 11, 14, 18, 29, 27) and offshore (samples 8, 15, 16, 19, 20, 24). Finally, chlorite contents of 2-4% were found nearshore (samples 1, 4, 6, 22, 28). In C1, chlorite content varied from 5-7%, with an average of 5.4 %. Chlorite content of 6-7% was found in the top, middle, and bottom of the core, while 5-6% content was mostly found from the top to the bottom of the core. In C2, chlorite content varied from 5 to 7% and averaged 6.0%. Contents of 5% and 7% were not as abundant as 6%. Chlorite content in core and surface sediments did not differ significantly among stations and layers (Fig. 3D).

Quartz was the most abundant mineral in surface and core sediments. Surface sediments contained 26-79% quartz and 50.5% on average, with 60-79% contents found mostly nearshore (samples 1, 2, 6, 22, 27, 28), 40-60% contents found nearshore (samples 3, 5, 7, 10, 11, 12, 17, 18, 23, 29, 30) and offshore (samples 8, 16, 19, 20, 24), and finally contents of 26-40% were mostly found offshore (samples 9, 13, 15, 21, 25, 26), with one instance nearshore (sample 14). In C1, content ranged from 32-48% with an average of 41.3%. Quartz contents of 45-48% and 40-44% were found divided into the upper, middle, and lower sections. Meanwhile, contents of 32-39% were found distributed from top to bottom. In C2, the content range of quartz was 35-51%, with 42.7% on average. Quartz contents of 45-51% were found divided into upper, middle, and lower sections, while 40-44% content was found distributed from top to bottom and 35-39% from top to middle (Fig. 3E).

Feldspar was found on the surface and within two sedimentary cores. In surface sediments, feldspar contents ranged from 3 to 16%, averaging 6.9%, with 11-16% distributed nearshore (samples 18, 29) and offshore (samples 13, 15, 16, 25), 5-9% distributed nearshore (samples 1, 2, 3, 5, 7, 11, 17, 22, 23, 27) and offshore (samples 8, 9, 19, 20, 24, 26), and 3-4% content found distributed nearshore (samples 4, 6, 10, 12, 14, 28, 30) and offshore (sample 21). In C1, feldspar contents of 3-7% were found distributed with an average of 4.8%. The highest contents of 6-7% were found distributed at the top, middle, and bottom of the core. Meanwhile, 5% content was found mostly at the top, middle, bottom and 3% content was found in some layers at the top, middle, and bottom of the core. In C2, the feldspar content range was 3-13% with an average of 6.2%. Feldspar contents of 7-13% were found distributed between the top and middle of the core, and 3-6% content was found distributed among the top, middle, and bottom of the core (Fig. 3F).

Goethite contents ranged from 3 to 7%, averaging 4.7%, in surface sediments with contents of 6-7% found distributed nearshore (samples 3, 7, 17, 22). Goethite content of 5% was found both nearshore (samples 1, 2, 5, 6, 11, 12, 14, 18, 23, 30) and offshore (samples 19, 20, 24). Goethite contents of 3-4% were found distributed nearshore (samples 4, 10, 27, 28, 29) and offshore (samples 8, 9, 13, 15, 16, 21, 25, 26). In C1, goethite content ranged from 2-4% with an average of 3.2%. Contents of 3% and 4% were the most common, while 2% content was uncommon. In C2, the range was also 3-4%, with an average of 3.6%, and goethite content of 4% was found distributed mostly from the middle to bottom of the core (Fig. 3G).

Halite content ranged from 0-3% in surface sediments with 1.8% average content. Halite contents of 2-3% were found distributed both nearshore (samples 3, 7, 12, 14, 22, 23, 29, 30) and offshore (samples 8, 9, 13, 15, 19, 20, 24, 25, 26), contents of 1-1.5% were found distributed nearshore (samples 1, 2, 4, 5, 6, 10, 11, 18, 28) and offshore (samples 16, 21), with some nearshore samples (17, 27) found without halite. Halite contents from 0 to 2% for C1 and C2, respectively, were found, averaging 0.8% in

C1 and 1% in C2. Halite content of 2% in both C1 and C2 was mostly found distributed from the middle to the bottom of the core (Fig. 3H).

Calcite and aragonite were carbonate minerals formed from biological materials. In surface sediments, they spread far from the shore and their content was often high, up to 11%, the content of 5-11% distributed mostly offshore (9, 19, 21, 26, 24, 25) and nearshore (14), the content 1-4 % were distributed nearshore (1, 2, 5, 6, 7, 11, 22, 23) and offshore (8, 13, 15, 16, 20), and some nearshore stations did not contain calcite and aragonite (3, 4, 10, 12, 17, 18, 27, 28, 29, 30). C1 had some layers with a content of 3-9% (17.0, 36.5, 42.5, 48.5cm), the remaining layers did not contain calcite and aragonite. In C2, calcite and aragonite were not present (Fig. 3I).

Gibbsite was absent from surface sediments and only found in C1 and C2 and the content was less than 4%. In C1, contents ranged from 1 to 3%, with an average of 2%. Gibbsite content of 2% was more common than 3 and 1% content. For C2, gibbsite content ranged from 0 to 2%, with an average of 0.4%, and contents of 1 and 2% were found distributed only in a few layers, most layers did not appear to contain gibbsite (Fig. 3J).

Pyrite was present only in the C1 and C2 cores and absent in surface sediments. In C1, pyrite content ranged from 0 to 4% with an average of 2.6%. Pyrite content of 2% was most common and spread lower than 3% and 4% contents. In C2, pyrite content averaged 2.8% with a range of 2-4%. Pyrite contents of 2% and 3% were common. Both C1 and C2 contained pyrite of high content below the surface layer (Fig. 3K).

3.3. Correlation between sediment parameters

In surface sediments, the parameters showed both negative and positive correlation (Fig. 4A). There was a strong positive correlation among illite and kaolinite and chlorite (R=0.84); moderate correlation (R=0.50-0.57) was found among halite and illite, kaolinite, chlorite, Md and S_k, and halite and calcite; and there was a weak correlation (R=0.38-0.43) between quartz and Md, S_k, gothite and S_0, and calcite and chlorite. There was a strong negative correlation between quartz and illite, kaolinite and chlorite (R ranging from -0.84 to -0.92); a moderate correlation (R ranging from -0.52 to -0.64) was found between Md and illite, kaolinite, quartz and halite, calcite; and a weak correlation was found between halite and Md, S_0, S_k, and kaolinite and S_k, and Md and chlorite.

In C1, there was no strong positive correlation, however there was a moderate correlation (R=0.57-0.64) between illite and kaolinite, chlorite; there was a weak correlation between kaolinite and chlorite, and between S_0 and quartz (R=0.40). There was no strong negative correlation, however, a moderate correlation (R ranging from -0.66 to -0.73) was found between quartz and illite and kaolinite, and between S_0 and S_k; there was a weak correlation between chlorite and quartz, goethite, and between kaolinite and calcite (Fig. 4B).

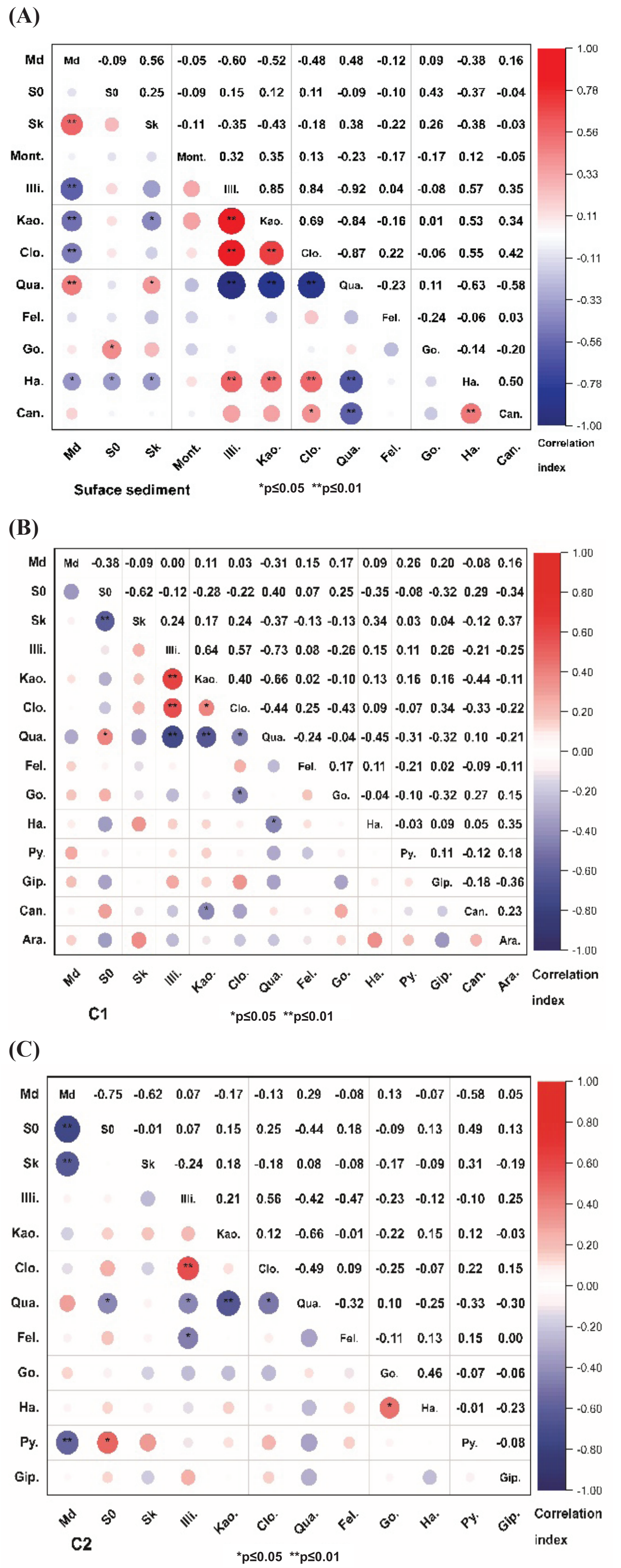

Fig. 4. (A-C) Correlation matrix between sediment parameters.

In C2, there was a moderate positive correlation found between illite and chlorite (R=0.56); a weak correlation (R=0.46-0.49) between halite and gothite, and between pyrite and S_0. A moderate negative correlation (R from -0.58 to -0.75) was found between Md and S_0, S_k and pyrite, and between kaolinite and quartz. There was a weak negative correlation (R ranging from -0.42 to -0.49) between quartz and S_0, illite, chlorite, and between illite and quartz, feldspar (Fig. 4C).

3.4. Characteristic sediment groups

Based on grain sizes and minerals, clustering techniques were used to divide the surface sediments of the Gulf of Tonkin into three groups with different characteristics (Table 2, Fig. 5). Group 1 consists of 7 stations located mainly nearshore (samples 1, 2, 4, 6, 22, 27, 28), which were fine sand, poorly sorted, symmetrically skewed, and containing low contents of illite, kaolinite, chlorite, felspar, calcite, halite, and a high content of quartz. Group 2 had 15 stations, which were divided into nearshore stations (samples 3, 5, 7, 11, 12, 17, 18, 23, 29, 30) and offshore stations (samples 8, 16, 19, 20, 24). This group had very coarse silt, were very poorly sorted, fine skewed, and contained illite, kaolinite, chlorite, halite, feldspar, and calcite. The contents most minerals of Group 2 were higher than those in Group 1, while the quartz content in Group 2 was lower than that of Group 1. Group 3, with 8 stations, was the most abundant of the offshore stations (samples 9, 13, 14, 15, 21, 25, 26) and nearshore (sample 10); they had very coarse silt, were poorly sorted, and very fine skewed. This group consisted of illite, kaolinite, chlorite, feldspar, calcite, and aragonite, were higher in content than those of Groups 1 and 2. However, quartz and goethite contents were lower than Group 1 and 2 (Table 2). Groups of sedimentary parameters were divided into three groups: Group 1 (Md, S_0, S_k, quartz, goethite) represents a strong environment (a zone where land and sea have strong interaction), Group 2 (montmorillonite, illite, kaolinite, chlorite, halite, and calcite), which represents a quiet environment (a zone where land and sea have a weak interaction), and, finally, Group 3 (feldspar) represents a mixed environment (Fig. 5).

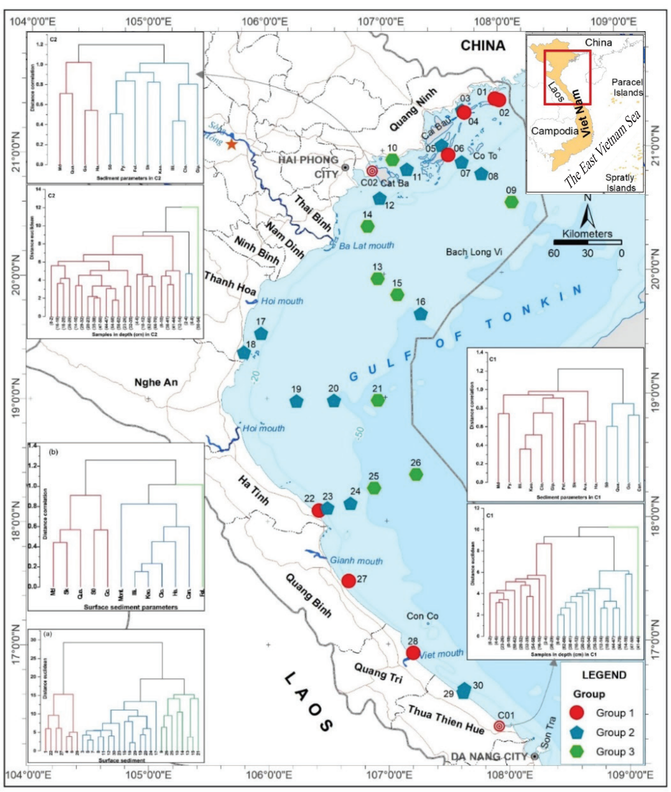

Fig. 5. Distribution of sediment groups.

Table 2. Grain sizes and mineral compositions in groups of sediment.

Position	Group	Number of stations	Sediment parameters			Content (%) of minerals											
			Md (mm)	S_0	S_k	*Mont.*	*Illi.*	*Kao.*	*Clo.*	*Qua.*	*Fel.*	*Go.*	*Ha.*	*Can.*	*Ara.*	*Py.*	*Gip.*
Surface	1	7	0.134	2.57	0.05	0	7	4	3	70	6	5	1	1	0	-	-
	2	15	0.059	4.42	-0.26	0	15	10	5	50	7	5	2	2	0	-	-
	3	8	0.054	3.37	-0.37	1	19	15	6	35	8	4	2	5	1	-	-
C1	1	11	0.049	2.05	-0.26	-	22	16	6	37	5	3	1	0	0	3	2
	2	13	0.045	2.18	-0.33	-	18	14	5	45	5	3	0	0	0	2	2
	3	1	0.048	2.10	-0.24	-	16	14	5	39	4	4	2	2	7	4	1
C2	1	22	0.033	2.66	-0.22	-	21	13	6	42	6	4	1	-	-	3	0
	2	2	0.027	3.01	-0.08	-	18	13	6	41	13	3	1	-	-	3	1
	3	1	0.040	2.25	-0.31	-	20	6	6	51	6	4	0	-	-	2	0

C1 had three groups with different characteristics (Table 2). Group 1 had 11 samples (layers) from the top to the middle of the core, had the highest Md, and were poorly sorted and fine skewed. Contents of illite, kaolinite, and chlorite were higher in Group 1 than in Groups 2 and 3, while quartz was the lowest. Group 2 had 13 samples (layers) mostly found distributed near the bottom of the core, and in some layers near the top and middle. Mineral contents of illite, kaolinite, chlorite, and pyrite were lower in Group 2 than in Group 1, while quartz was the highest. Group 3 had only one sample (layer) distributed in the middle core, containing calcite, aragonite, pyrite, halite, and goethite contents that were higher in this group than in Groups 1 and 2. The contents of other minerals were lower. Sediment parameters were divided into two groups: Group 1 (Md, pyrite, illite, kaolinite, chlorite, gibbsite, feldspar, S_k, aragonite, halite) indicating a quiet environment, and Group 2 (S_0, quartz, goethite, calcite), indicating a more dynamic environment.

There were three sediment groups in C2 (Table 2). Group 1 consisted of 22 samples (layers) that were distributed from the top to the bottom of the core; those sediments had very coarse silt, were poorly sorted, and fine skewed. The contents of illite, kaolinite, and chlorite were high. Group 2, with 2 samples (layers) distributed near the top (2-4 and 6-8 cm), had coarse silt, was poorly sorted, and symmetrically skewed. Mineral contents of feldspar, illite, quartz, and gibbsite were different from those in Groups 1 and 3. Group 3 had only one sample (layer) near the end of the core (50-54 cm) and had a high quartz and low kaolinite content.

4. Discussion

The dynamics of the sedimentary environment are reflected in the distribution of grain size and mineral composition grouped by similarity of grain size and mineral composition. The Gulf of Tonkin is vast, with many conditions affecting the sedimentary environment. The characteristics of surface sediments allow us to understand the bay, while the characteristics of sedimentary cores help understand the local sedimentary environment.

Surface sediments were divided into three groups with different characteristics. The strong dynamic group (Group 1) was distributed nearshore with fine and very fine sand, poorly sorted, and symmetrically skewed. Quartz was the most abundant mineral at 70%, while illite, kaolinite, and chlorite contents were lower. The weak dynamic group (Group 2) was distributed around the nearshore and offshore regions, it had very coarse silt, was very poorly sorted, and fine skewed. Mineral contents of illite, kaolinite, and chlorite increased significantly, and sediments of biological origin increased due to the presence of calcite. The quiet dynamics group (Group 3) was distributed offshore, had very coarse silt, was poorly sorted, and very fine skewed. The contents of montmorillonite, illite, kaolinite, and chlorite were higher than in the previous groups, while the quartz content reduced significantly and marine and biological sediments increased by calcite, aragonite, and halite present. There were four factors (FA) affecting surface sediments, ranging from 10.81 to 40.42% (Table 3). FA1 was 40.42% and indicated Md, S_k, illite, kaolinite, chlorite, quartz, and halite. FA 2 was 14.90% for S_0 and goethite. FA3 was 11.81% for calcite, and FA4 was 10.81% for feldspar and montmorillonite (Table 3). FA1 consisted of sediments supplied by mechanical weathering and erosion of mother rocks from the mainland and islands eroded by the presence of illite, kaolinite, chlorite, and quartz in surface sediments, under the influence of rivers and sea currents distributed in the bay. In addition, FA1 was influenced by environmental and oceanic physico-chemical factors such as waves, currents, tides, and salinity by the presence of Md, S_k, and Halite. FA2 reflects sediment sorting that influences goethite formation through geochemical processes. FA3 reflects that surface sediments had another sediment source from biological material through the presence of calcite. FA4 was affected by montmorillonite and feldspar, indicating sediments from weathering of mother rocks.

The correlation among sedimentary parameters in surface sediments reflect the relationship of sediment supplies, environmental dynamics, and form minerals. The same sediment supplies are shown by the positive correlation between illite, chlorite, and kaolinite. Environmental dynamics are shown between Md and S_k, quartz, illite, chlorite, and kaolinite. The mineral formations are demonstrated by the positive correlation of halite and gothite with S_0, illite, chlorite, kaolinite, and calcite (Fig. 4A).

Table 3. Sediment parameters and factors' effect on sediments.

N_0	Parameters	Surface sediment				C1				C2			
		FA1	*FA2*	*FA3*	*FA4*	*FA1*	*FA2*	*FA3*	*FA 4*	*FA1*	*FA2*	*FA3*	*FA4*
1	Md	-0.63	0.00	0.65	-0.07	0.27	0.29	0.41	-0.58	-0.73	0.52	0.21	-0.07
2	S_0	-0.01	0.83	-0.15	0.25	-0.62	-0.45	0.31	0.11	0.75	-0.19	0.12	-0.19
3	S_k	-0.51	0.44	0.48	0.03	0.50	0.47	-0.40	0.33	0.24	-0.60	-0.50	0.32
4	Mon.	0.29	-0.02	-0.07	-0.71	-	-	-	-	-	-	-	-
5	Illi.	0.93	0.20	-0.05	-0.03	0.75	-0.30	0.16	0.16	0.31	0.79	-0.16	0.33
6	Kao.	0.88	0.24	-0.05	-0.22	0.72	-0.16	0.18	-0.04	0.53	0.14	0.10	0.49
7	Clo.	0.86	0.17	0.10	0.23	0.68	-0.39	-0.03	0.25	0.55	0.52	-0.02	-0.13
8	Qua.	-0.96	-0.09	-0.13	-0.15	-0.84	-0.22	-0.39	-0.03	-0.80	-0.32	-0.37	-0.06
9	Fel.	0.12	-0.40	-0.17	0.74	0.13	-0.15	0.65	0.30	0.23	-0.26	0.39	-0.67
10	Go.	-0.18	0.74	-0.08	0.05	-0.36	0.32	0.66	0.02	-0.31	-0.21	0.62	0.22
11	Ha.	0.73	-0.25	0.26	-0.15	0.40	0.49	0.07	0.35	0.08	-0.22	0.79	0.36
12	Py.	-	-	-	-	0.24	0.20	-0.02	-0.70	0.64	-0.40	-0.09	-0.10
13	Gib.	-	-	-	-	0.48	-0.30	-0.11	-0.28	0.16	0.47	-0.04	-0.38
14	Can.	0.48	-0.06	0.77	0.17	-0.45	0.32	0.19	0.21	-	-	-	-
15	Ara.	-	-	-	-	0.01	0.88	-0.06	0.06	-	-	-	-
Eigenvalue		4.85	1.79	1.42	1.30	3.76	2.20	1.55	1.38	3.06	2.23	1.66	1.30
Variance (%)		40.42	14.90	11.81	10.81	26.86	15.75	11.04	9.90	25.51	18.59	13.84	10.80
Cumulative variance (%)		40.42	55.32	67.12	77.93	26.86	42.61	53.65	63.52	25.51	44.09	57.93	68.73

The C1 core was in Tam Giang - Cau Hai Lagoon, which was a quiet environment with four factors affecting the sedimentary environment from 9.90 to 26.86% (Table 3). FA1 was 26.86% by S_0, S_k, illite, kaolinite, chlorite, and quartz. FA2 was 15.75% by aragonite. FA3 was 11.04% by feldspar and goethite. FA4 was 9.90% by Md and pyrite (Table 3). FA1 indicated weak dynamics, showing a combination of S_0, S_k, illite, kaolinite, chlorite, and quartz. The origin of illite, kaolinite, chlorite, and quartz was from the erosion and weathering of rocks around the lagoon. FA2 indicated source sediment supplied from biological materials by the presence of aragonite (Group 3). FA3 indicated physiochemical factors that formed goethite (Group 2). FA4 indicated Md factors affecting pyrite formation.

Correlation in C1 reflects sediment supplies, dynamic conditions, and mineral formation. Sediment supplies are shown by the positive correlation between illite, kaolinite, and chlorite. Environmental dynamics are shown by the negative correlation between quartz, S_0 and illite, kaolinite, chlorite, and S_k. The unfavourable factors for the formations of gothite, halite, and calcite are shown by the negative correlation between them with chlorite, quartz, and kaolinite (Fig. 4B).

In C2, which was taken from the Bach Dang estuary, were four factors affecting the sedimentary environment ranging from 10.8 to 25.51%. FA1 was 25.51% by Md, S_0, kaolinite, chlorite, quartz, and pyrite. FA2 was 18.59% by S_k, and illite. FA3 was

13.84% by halite and goethite. FA4 was 10.8% by feldspar (Table 3). FA1 indicated a weak environment with Md, S_0, kaolinite, chlorite, quartz, and pyrite, with source sediment provided by weathering process of kaolinite, chlorite, and quartz, in addition to the formation of pyrite. FA2 reflected a quiet environment by the deposition of illite and S_k. FA3 indicated the advantage of forming goethite and halite. FA4 indicated the source of feldspar.

The correlation between sediment parameters in C2 shows sediment supplies through the positive correlation between chlorite and illite. Environmental dynamics are shown through Md, S_0, S_k, quartz, and feldspar with illite, kaolinite, and chlorite. Formation of minerals was shown by the positive and negative correlation of pyrite, halite, and gothite with Md and S_0 (Fig. 4C).

5. Conclusions

In the Gulf of Tonkin, surface sediments were found distributed with very fine sand > fine sand = very coarse silt = medium silt > coarse silt. In C1, very coarse silt was distributed across all cores. C2 contained very coarse silt > coarse silt > medium silt. The average mineral content of the sediments was quartz > illite > kaolinite > chlorite > feldspar > goethite > pyrite > halite > calcite > gibbsite > aragonite.

There were three groups of surface sediments with different properties. Group 1 was distributed nearshore and is characterized by a strong environment evidenced by fine sands with high quartz content and low illite, kaolinite, and chlorite content. Group 2 was distributed nearshore and offshore and is in a characteristically weak environment evidenced by very coarse silt, increasing contents of illite, kaolinite, and chlorite, and decreasing quartz content. Group 3 was distributed nearshore and offshore with a characteristic quiet environment as evidenced by the highest content of illite, kaolinite, chlorite, and calcite, and the lowest content of quartz. Both C1 and C2 are characteristically weak environments found in the Tam Giang - Cau Hai lagoon and Bach Dang estuary, respectively, depositing very coarse silt, coastal silt, medium silt, and high contents of illite, kaolinite, and chlorite.

Sediment sources in the Gulf of Tonkin are primarily due to the weathering and erosion of formations from the mainland and islands carried by rivers, waves, currents, and tides through the presence of illite, kaolinite, quartz, chlorite, and feldspar. The presence of goethite, halite, and pyrite in the sediments suggested formation by geochemical processes. The presence of calcite and aragonite in the sediments reflects the origin of the biological material.

CRediT author statement

Dang Hoai Nhon, Nguyen Van Thao, Tran Duc Thanh: Conceptualization, Methodology; Dang Hoai Nhon, Lai Thi Bich Thuy, Nguyen Van Thao: Data curation, Investigation; Dang Hoai Nhon, Nguyen Dac Ve, Bui Van Vuong, Bui Thi Thanh Loan, Hoang Thi Chien, Duong Thanh Nghi: Writing - Original draft preparation; Nguyen Dac Ve, Dang Hoai Nhon: Software, Validation; Dang Hoai Nhon, Tran Duc Thanh: Writing - Reviewing and Editing.

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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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