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Quaternary Sedimentary Cyclic in relation to the Global Sea Level Changes in the Red River Delta of Vietnam

Tran Nghi[1], Tran Thi Thanh Nhan[1], Trinh Hoai Thu[2], Dinh Xuan Thanh[1], Do Tien Hung[3], Nguyen Thị Huyen Trang[1], Tran Thi Dung[1], Nguyen Thi Phương Thảo[1]

[1]*VNU - University of Sciences*
[2]*Institute of Marine Geology and Geophysics - VAST*
[3]*The Union of Science Geology and Water Resources, Hanoi, Vietnam*
Corresponding author: tranhnghi@gmail.com

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Abstract: *The content of the article introduces the evolutionary history of Quaternary sediments of the Red River Delta taking place in 5 cycles based on analysis and comparison of the sedimentary composition of 2 boreholes BH4-HN in the Gia Lam area (Ha Hoi City). Noi and BH56-ND Hai Hau area (Nam Dinh province). In both Quaternary boreholes, there are 5 cycles with a causal relationship with 5 cycles of global sea-level change due to the influence of 5 glacial/interglacial cycles: (1) Gunz/G-M has an early Pleistocene age (Q_1^1); Mindel /M-R has early middle Pleistocene (Q_1^{2a}); Rise/R-W1 has late middle Pleistocene (Q_1^{2b}); Wurm1/W1-W2 has early late Pleistocene (Q_1^{3a}); Wurm2/Flandri transgression has late late Pleistocene to Holocene (Q_1^{3b}-Q_2). Each cycle is characterized by three facies complexes: (1) the lowstand alluvial gravelly sand facies complex (SgarLST); (2) the transgressive lagoon sandy mud and mud facies complex ($M_s$amt, mtTST); (3) the highstand deltaic facies complex ($M_s$amhHST). However, comparing the two boreholes BH4-HN and BH56-ND, the difference is seen as follows: (1) for borehole BH4-HN, the sediment thickness of the cycles tends to decrease gradually from Pleistocene to Holocene, while the borehole BH56-ND has the opposite variation; (2) in Pleistocene cycles C2, C3, and C4 have a thickness similar to these 3 cycles in borehole BH4-HN; (3) Cycle C5 of BH56-ND has a thickness of 56m, a sudden increase compared to 30m in borehole BH4-HN. During the Pleistocene period on the entire plain, tectonic subsidence occurred with uniform amplitude and during the Holocene in the Nam Dinh area, i.e. downstream river channel, the subsidence amplitude was more than in the Hanoi area, i.e. the midland river channel.*

1. Introduction

The Red River Delta is one of the two largest deltas in Vietnam, after the Mekong River Delta in the South. The delta is triangular-shaped, which starts from Viet Tri and is widened toward the sea. The Red River Delta is created by the Red River, Day River, and Thai Binh River systems (Figure 1). Previous works all demonstrate that the Formation of the Red River Delta has been closely associated with the tectonic evolution of the Ailao Shan-Red River Shear Zone, which was resulted from the India-Eurasian collision during the Cenozoic [A.Replumaz. and P.Tapponnier. 2003].

Due to some tectonic events, which occurred during the Cenozoic, the Red River Delta together with its larger structure has been uplifted and experienced a very strong erosional process at the End of the Miocene. This change has led to the formation of a regional unconformity, which separates the overlying Pliocene-Quaternary horizontal-lying sedimentary formation from the underlying Miocene strongly faulted, folded, and eroded formation (Figure 2).

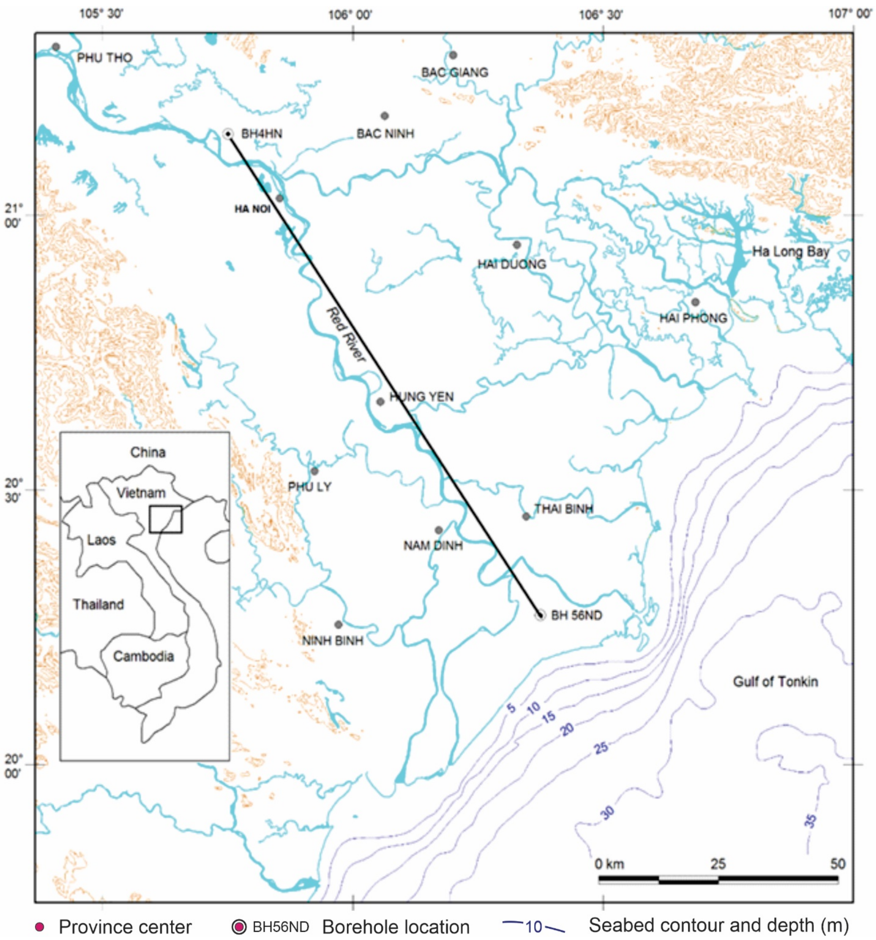

Figure 1. *Location of the study area*

It is noted that the tectonic subsidence of the Red River Delta became quiescent during the Quaternary period while the eustatic sea level of the region has generally fallen since the Early Pliocene, before the Last Glacial Maximum (at the depth of 100m water below present-day sea level) and was followed by a rapid sea-level rise during the last from 18-5ka BP (Lieu 2006; Tanabe et al. 2003a). It means that sea-level variation and paleo-climatic conditions are considered the most important factors controlling depositional environments and associated lithofacies of the Red River Delta during the Quaternary Period.

There have been several thematic studies focusing on the Quaternary sediments of the Red River Delta during carrying out 1:200.000 and 1:50.000 scaled geological mapping (Ky 1973, 1978; Toan 1989). Results of these works allowed the Vietnamese stratigraphers to establish 05 Quaternary units: (1). Early Pleistocene Hai Duong Formation ($Q_1^1\ hd$), (2). Middle-Late Pleistocene Hanoi Formation ($Q_1^{2-3}\ hn$), Late Pleistocene Vinh Phuc Formation ($Q_1^{3b}\ vp$), Early-Middle Holocene Hai Hung Formation ($Q_2^{1-2}\ hh$), and Late Holocene Thai Binh Formation ($Q_2^3\ tb$) (Ky 1978; Toan 1995). The Hai Duong Formation was subsequently renamed the Le Chi Formation ($Q_1^1\ lc$) based on the recently updated data from more detailed geological mapping (Khien 2003).

However, the establishment and subdivision of these formations were simply based on petrographic data with no supportive absolute age constraint. As a consequence of lacking data, the stratigraphic boundaries were only predictively picked.

While the Quaternary sediments distributed within the Red River Delta plain were studied and subdivided into 05 stratigraphic units based on the direct description and petrographic data derived from numerous shallow drilling cores, the stratigraphy of the nearshore zone was only based on the high-resolution seismic interpretation. Mathers and Zalasiewicz 1999; Nghi et al. 2004b; Nghi et al. 1991; Nghi et al. 2002; Tanabe et al. 2003a; Tanabe et al. 2006; Van den Bergh et al. 2007, and Funabiki et al. 2007 used sedimentary composition, physical properties, and ^{14}C dating data to subdivided the coastal Quaternary sediments into 3 sedimentary units, namely: Unit 1 is composed of the coastal marshy sediments, whose age varies from 12 ka to 7 ka BP; Unit 2 consists of embayment greenish gray clay deposited during from 7ka to 5ka BP; and Unit 3 demonstrates the latest deltaic clayish silt (accumulated from 5ka BP to present day) (Mathers and Zalasiewicz 1999; Nghi et al. 2004a; Nghi et al. 2002; Tanabe et al. 2003b; Tanabe et al. 2006; Van den Bergh et al. 2007).

Application of high-resolution seismic data to sequence stratigraphy was conducted by Doan D.L., (2003) to reconstruct the Holocene sequence stratigraphy of the Red River Delta and three systems tracts were defined from these studies. Subsequestudied Holocene sediments throughout the Red River territory and reproduced the sedimentary environment in the Flandrian transgressive phase and the late Holocene regressive phase (Lam 2003; Lieu 2006). However, the authors still have not focused on lithofacies analysis based on the combination of sediment parameters and environmental geochemical index so it does not clarify the cross-boundary between the lowstand systems tract (LST) and the transgressive systems tract (TST), between the transgressive systems tract (TST) and highstand systems tract (HST) about sea-level change.

On the other hand, nearly ¼ Vietnamese population are living in the Red River Delta plain, which is fully overlain by the Quaternary unconsolidated sediments. It means that any change in the area will strongly affect human livelihood. Especially, strong coastal erosion has occurred along the delta coast during the recent decades. Although there are some reasons explained for this intensified coastal hazard, the majority of the geoscientists reckon sea level rise and starvation of the sediment supply are the main causes (Nghi et al. 2011; Nghi and Tiep 1993) . If this interpretation is correct, the relative sea-level change will result in not just variation of the coast but also switching sedimentary depositional system according to the erosion or extension of the delta. This causal relation allows us to decipher the connection between sedimentary cycles and sea-level fluctuations through time and hence the evolutionary history of the delta system will be reconstructed. It is important not only for the scientific purpose but also for the prediction of the Red River delta change in the future.

Although the region has attracted many researchers working on the geological evolution of the Red River Delta, their sedimentary cyclicity and how it is linked to the relative sea-level change during the Quaternary Period are still poorly understood.

The main objective of this work is to define how the relative sea level has controlled cyclic sedimentation of the Red River Delta during the Quaternary period as one of the most important pieces of evidence for the prediction of the delta variation under a heavy impact of the rapid sea-level rise soon.

2. Geological setting

2.1. Tectonic feature

As mentioned in the previous section of this work, the Red River Delta is an NW extension of the main Red River Basin, which has been produced by a tectonic collision between the Indian and Eurasian Plates as well as by a transtensional deformation along the Red River Shear Zone since the Early Cenozoic (A.Replumaz. and P.Tapponnier. 2003). As the result, the study area is mainly controlled by a series of striking faults by running in the direction NE-SE (Figure 2).

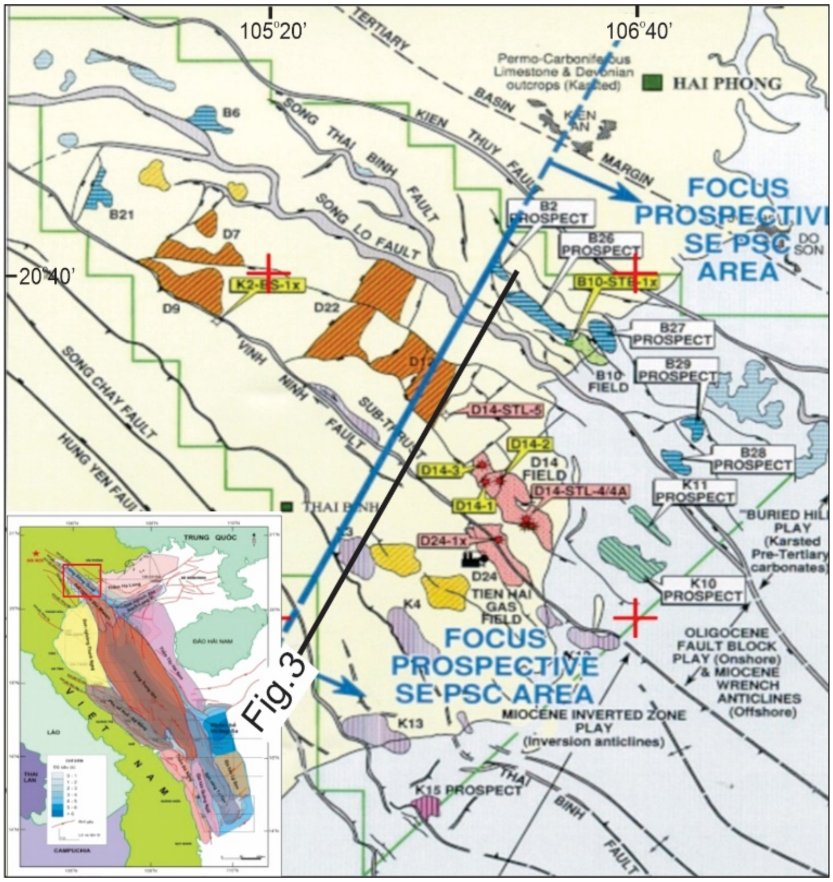

Figure 2. *The main geological structures of the study area (according to Ạnjoil, 1996 & PIDC,2004).*

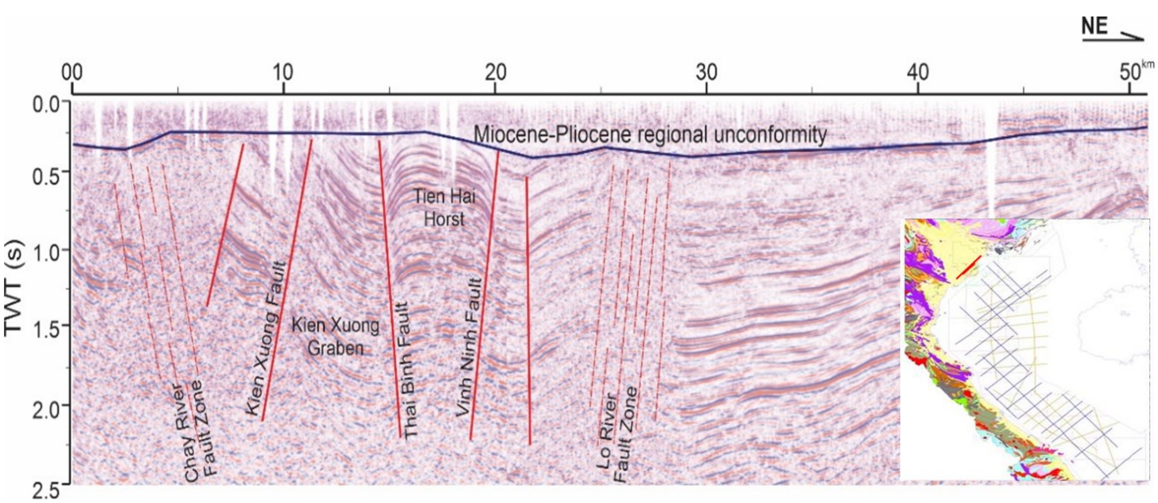

Figure 3. *Combine seismic profile showing the geological structure of the study area*

Due to a strong and rapid extension process occurred during the Eocene (?)-Early

Miocene Epochs, the study area is subsided and quickly filled by the clastic sediments, which are now known as the Eocene (?)-Early Miocene syn-rift formation. The depocenter elongates in the NW-SE direction and is characterized by the thickest sediment sections in the deepest part of the region. This rifting process was subsequently followed by gradual thermal subsidence to form the Middle-Late Miocene coal-bearing formations (Figure 3).

(Data source: Coal Resources assessment of the Onshore Red River Basin)

Especially, a tectonic inversion that occurred in the Late Miocene has led to the formation of a regional unconformity, which separates the overlying Pliocene-Quaternary formation from the older sedimentary rocks (Figure 3). In addition, the pre-existing transtensional faults have been reactivated in a compressional regime to produce a successive graben and horst. It is noteworthy to indicate that, no significant tectonic activities have taken place since the Pliocene time. This observation is evidenced by the steady thickness and horizontal structure of the Pliocene-Quaternary sedimentary formation on the Red River Delta Plain (Figure 3). This implies that sea level is likely to play an important role in constraining sedimentation of the Red River Delta during this time.

2.2. Stratigraphy

Stratigraphy of the Red River Delta has been studied by some Quaternary geoscientists, most of the classification schemes were based on the direct core description, thin section examination, granulometric analysis, paleontological constraints, etc. Although there have been numerous exploration wells conducted by oil and gas companies, no core for the Pliocene-Quaternary section was collected as it is not an interesting object for the oil and gas industry. Therefore the data derived from these well were not much help for this study.

The recent shallow drill holes have allowed us to conduct more detailed analysis at a much higher resolution. As the result, the Quaternary stratigraphy of the Red River Delta was subdivided into 05 units, which are described from the bottom to the top of the section as follow:

- Early Pleistocene Le Chi formation (Q_1^1 *lc*): it is the lowest Quaternary Formation, which extends over 40m thick. The unit was subdivided into two sedimentary sections: (1). The lower section consists of clayish poly mineral pebbles; (2) the upper section is composed of sandy silt deposited in an embayment and/or lagoonal environments.
- Middle-Late Pleistocene Hanoi Formation (Q_1^{2-3}*hn*): The formation is 800m thick and consists of fluvial pebbles, gravel, and coarse sand (30m - 50m thick) intercalated with thinly bedded clayish silt (5 -15m);
- Late Pleistocene Vinh Phuc Formation (Q_1^{3b} *vp*): This Formation demonstrates 50m thick and was splitted into 2 sedimentary sections: (1). The lower section is dominated by fluvial sandy sediments (20-30m thick); and (2) the upper section is characterized by the mottled clay of ~10-20m thick. Early-Middle Holocene Hai Hung Formation (Q_2^{1-2} *hh*): The formation thickness is 20m. The lower section of this Formation comprises muddy sediments of the coastal swamp environment while the upper section is mainly composed of greyish-green clay.
- Late Holocene Thai Binh Formation (Q_2^3*tb*): This is the youngest formation of 15m thick overlying the pre-existing units. The Thai Binh Formation consists of two different sections: The lower section contains sandy clayish silt of deltaic plain environment while the upper section is dominated by the alluvial sand and clayish silt.

3. Materials and study methods

3.1. Materials

To conduct this work the authors use the following data sources:

- Core loggings of the borehole BH-4HN (in Gia Lam District, Hanoi City - 21°30’N, 105°45’E) (Figure 1). The borehole was drilled down at the depth of 125m, which penetrated through the Lower Quaternary boundary.

- Core loggings of the borehole BH-56ND (in Hai Hau District, Nam Dinh Province - 20º30'N, 106º20'E) (Figure 1), The borehole reaches at the depth of 185m and is drilled through the Quaternary/Pliocene boundary at the depth of 180m.

- Samples were collected from the two boreholes for the granulometric analysis (grain-size: 230 samples; Roundness (Ro): 100 samples)), artificial thin section examination (120 samples) and geochemical analysis (pH: 80 samples; Eh: 80 samples and Kt: 80 samples).

3.2. Study methods

3.2.1 Physical property analysis

- Grain size statistics method

The grain size analysis of the sediments was conducted by using dry and wet sieving and pipet technique. The sieving technique was effectively applied to coarse-grained and incohesive fractions, whose diameters are larger than 0.063 mm. In contrast, the finer sediment grains are commonly cohesive or possess electrostatic charges, which make them unsuitable for dry sieving. The most widely used analytical technique for muddy sediments is the pipette method. This is a form of "sedimentation" analysis because the particle size is indirectly computed based on the falling rate of particles in a water environment.

Diameters of grain size used in this article are according to Φ units: Φ = -log2d (Krumbein 1934, 1938).

Trask P.D, 1932 proposed calculating the three important coefficients based on the cumulative construction curve in diameter (mm) are:

- *The Median value:* $Md = Q_{50}$ *(mm); (1)*

- *The sorting coefficient:* $So = \sqrt{\frac{Q_{25}}{Q_{75}}}$ *(2)*

- *The asymmetric coefficient:* $Sk = \frac{Q_{25} \cdot Q_{75}}{Md^2}$ *(3)*

where Q_{25}, Q_{50}, and Q_{75} are computed from statistic analysis and accumulative curve of the grain size distribution [Trask 1932].

The sorting coefficient (So) is very important in lithofacies analysis. According to Rukhin (1969): So = 1-1.58 demonstrates good sorting, typical for wave-dominated tidal flat sand facies, river mouth sand bar facies, and sandy barrier; So = 1.58-2.12 implies medium sorting, typical for downstream river channel, deltaic plain environment and So > 2.12 suggests that the sediments are deposited in the flood plain, delta plains and mixed tidal flat environments (Rukhin 1969a).

Roundness coefficient (Ro) is the characteristic for the morphology of sharp particles with sharp edges or rounded edges under the activity of the hydrodynamic regime of the environment, the transportation distance by the river, the intensity of the coastal wave dynamics, and geological time rounding debris. Calculation of the roundness coefficient has many methods (Nghi 2003, 2010, 2018; Wadell 1935), in this paper, the Ro coefficient was used according to the formula proposed by Nghi T., 2010 (Nghi 2010):

Ro = 1- 0.1n; (4)

Where n is the number of convex angles of the particle.

Ro varies from 0 (min) to 1 (max).

Ro is of great significance in lithofacies analysis and sedimentary environment. Ro = 0.0-0.3 indicates the deluvial and proluvial environments; Ro = 0.3-0.5 indicates the riverbed environment; while Ro = 0.5-0.7 demonstrate the deltaic tidal flats and river channel sand bar environment and Ro> 0.7 implies the wave-dominated tidal flat environment, estuarine sand bar and sandy barrier (Nghi 2010, 2018).

We further deduced another property, which is known as the gravel and Sand ratio (S coefficient) introduced by Nghi T. (2018). The coefficient is calculated by the following formula:

S = 1- M (5)

In which, 1 is the total percentage of sediments (100%); **S** is the percentage of pebble, gravel, and sand; **M** is wt. percentage of mud (silt and clay).

The S coefficient can be used to interpret the sedimentary environments based on the following scaling: S = 0-0.3 indicates the marsh and embayment - lagoonal environment; S = 0.3-0.6 shows the flood plain and delta plain environment; S = 0.6-0.8 demonstrates sand bar in the river channel, downstream river channel and tidal mixed flats environment while S = 0.8-1.0 reveals for the midland river bed environment, the estuarine sand bar (Nghi 2018).

- Artificial thin section examination

Unconsolidated sediments have been coalesced by epoxy resin to produce pseudo-sandstone. The sample was subsequently sliced and polished, before examination under a polarized microscope. This method is applied to determine quartz content (Q), feldspar (F), and rock fragments (R); where Q + F + R = 100%.

Then the sample was further examined by using a binocular microscope to accurately identify mineral composition and morphology such as monocrystalline quartz, polycrystalline quartz, plagioclase, potassium feldspar, fragments of metamorphic rock, siliceous rock, and eruption rock.

- Geochemical analysis

To constrain the paleo-depositional environment, in this study we used several common geochemical proxies as follow:

pH values were determined for the fine-grained sediments. When pH <7 indicates continental environment while pH = 7 indicates transition environment, and pH> 7 illustrates for the marine environment.

(2) Eh values were also determined for the fine-grained sediments. Eh <0 indicated the swamp environment.

The samples were analyzed by using Horiba LAQUA pH 1300 m, detection range varies from -2.0 to 19.9 pH with the precision of ± 0.003 while Eh measuring was set at: ± 2000mV; Resolution: 0.1mV; Accuracy: ± 0.23.

Analysis of cation exchange capacity (Kt)

Cation exchange capacity (Kt) is a geochemical parameter of the soil's ability to hold positively charged ions. The main ions associated with Kt in soils are the exchangeable cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) and are generally referred to as the base cations (Grim R.E. 1949). Major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) in sediments during exchange were determined by atomic absorption spectrometry (AAS) using a non-reacted CoHex (cobalt hexamine trichloride) solution as a reference.

$$Kt = \frac{K^{+} + Na^{+}}{Ca^{+2} + Mg^{+2}} \quad (6)$$

Kt is normally expressed in mgd/100 g (milliequivalents of charge per 100 g of dry soil) or cmolc/kg (centimoles of charge per kilogram of dry soil).

If Kt <0.5 it indicates the continental environment; Kt = 0.5-1.0 is for transitional environment and Kt >1 shows marine environment (Table 1).

Table 1. *Integration of lithofacies and lithological parameters and environmental geochemistry index*

Lithofacies complex	Facies	Md (mm) (average)	So (average)	Ro (average)	S (average)	pH	Eh (mv)	Kt
Delta plain lithofacies complex	Deltaic flood plain		2.5	-	0.4	7.3	>50	1.2
	Sand bar	>90	1.3	0.7	0.9	-	-	-
Coastal bay-lagoon lithofacies complex	Bay	-	2.0	-	0.1	7.8	50	2.0
	Coastal swamp	-	2.3	-	0.3	7.2	<0	1.5

Lithofacies complex	Facies	Md (mm) (average)	So (average)	Ro (average)	S (average)	pH	Eh (mv)	Kt
Alluvial lithofacies complex	Flood plain	-	2.7	-	0.5	6.5	200	<0.5
	River channel	<60	3.0	0.3	0.8	-	-	-

3.2.2. Lithofacies analysis

Each sedimentary lithofacies is characterized by a series of physical properties, mineral composition, geochemical indexes, and sediment dynamics, etc. In this study, we compare out computed values of Md, So, Ro, Q, S, pH, Eh, and Ht to the representative values of those parameters of each specific facies, which have been presented in many textbooks (Rukhin 1969b; Wadell 1935) (Table 1).

The lithological parameters and environmental geochemical index are indicators for the sedimentary environment. Identifying sedimentary environments is the most important task of lithofacies analysis. *Because sedimentary facies are association complex of petrographic composition and organisms are deposited in a certain environment different from the surrounding environment*. To divide the sedimentary cycles, it is necessary to analyze the lithofacies association vertically. To analyze the lithofacies association of the entire Quaternary sedimentary column in the Red River Delta, it must be based on lithological parameters, geochemical environmental indicators, pollen spores, and micro-paleontology. However, in the Pleistocene sediments of the Red River Delta, there are no spore pollen and micropaleontology so these 2 indicators are not used in lithofacies analysis. Each range of values of lithological parameters and geochemical parameters indicates a certain environment as mentioned above. Therefore, to correctly assert a disturbing environment, not only one parameter but also a combination of different parameters (Table 1).

In addition, the Quaternary sediments of the Red River Delta have been deposited in several lithofacies and depositional environments, which are characterized by typical colors. It means that analyzing the primary color of unaltered sediments may help interpret their paleodepositional environments and associated lithofacies.

- Delta plain clayey silt facies at the end of each cycle is *yellowish red-spotted color* due to infiltrated weathering (in the stratigraphic column of BH4-HN and BH56-ND denoted by symbol hashtag) (Figure 3, Figure 4, Figure 5, Figure 6, Photo 1);

- The coastal swam mud facies that create the peat before the maximum transgression at the middle position of each cycle is *black*;

- Bay-lagoon clay facies lying on swamp mud facies is *greenish-gray color.*

Lithofacies analysis based on the structure of sediments:

- River channel pebbles and sand facies are cross-bedding structures in the one direction;

- Tidal flat mud facies is with fine cross-bedding structure;

- Bay-lagoon greenish-gray clay facies is composed of horizontal and parallel bedding structures.

3.2.3. Sedimentary cycle-Sea level correlation

Richard, L. (2005) summarized the glacial cycles and the changes in sea levels, in 5 cycles during the Quaternary Epoch consisting of Gunz/G-M (1600-700 ka BP); Mindel/R (700-160kaBP); Riss/W1(160-70ka BP); Wurm1/W2 (70-30kaBP); Wurm 2/ Flandrian transgression (30ka BP up to now). The authors used this model to compare with 5 cycles of Quaternary sediments of the Red River Delta and found a perfect match (Figure).

We also applied the principles of sequence stratigraphy in establishing the linkage between the formation of lithofacies and related systems tracts of each sequence. Each sedimentary cycle is composed of 3 vertically asociation lithofacies complex: (1) alluvial lithofacies complex of lowstand regressive phase; (2) Transgressive coastal swamp and bay-lagoon lithofacies complex of transgressive phase; (3) The delta lithofacies complex of highstand regressive phase. At the same time, each sequence is also composed of 3 sedimentary systems tract: (1) Lowstand systems tract (LST) corresponds to the alluvial lithofacies complex; (2) Transgressive systems tract (TST) corresponds to the coastal swamp and bay-lagoon lithofacies complex. So the lithofacies and the sedimentary systems tract are the same product of the global sea-level change cycle.

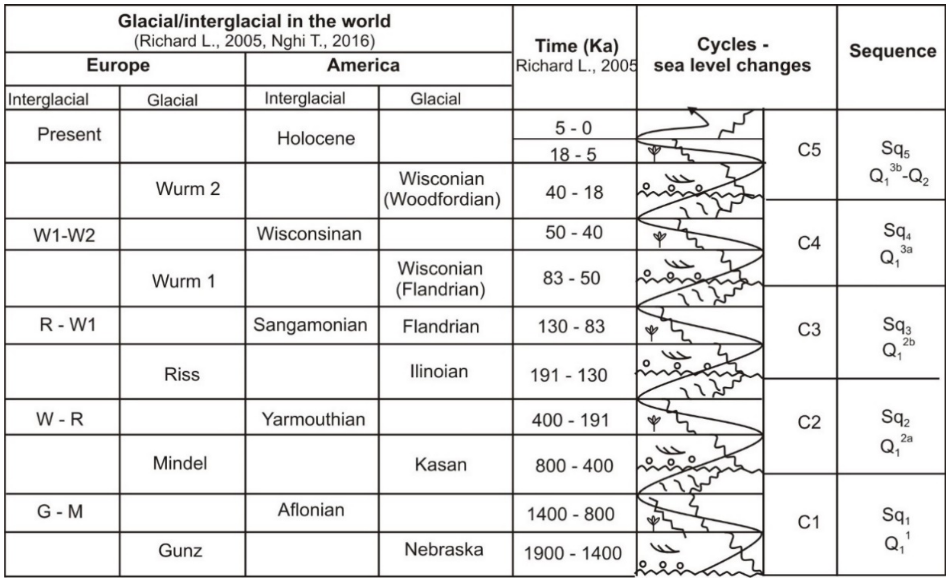

Figure 2.1. *Comparison of 5 global change cycles and glacial/interglacial in Europe and America (Little Richard ,2005; Tran Nghi, 2018)*

4. Results

4.1. Concept of sedimentary cycle

The sedimentary cycle is the repetition of vertical sedimentary units of the stratigraphic column that is related to the global sea-level change (Catuneanu 7th April 2006). Because very limited paleontological and absolute dating data were given to the Red River Delta area, the method of correlating sedimentary cycles to the glacial periods is likely effective in reconstructing the sedimentary evolution of the region.

The boundary of the sedimentary cycles can be selected according to either of the two options: (1) The boundary of the cycles is drawn at the bottom of the basal coarsest grain layer in a sedimentary succession; (2) The boundaries are drawn at the bottom of the finest grain layer in a sedimentary stratigraphic unit. In this study, the authors chose option 1. This alternative cycle boundary coincides with the unconformity of the stratigraphy and corresponds to the periods of minimum regression due to the influence of glacial phases such as Gunz, Mindel, Riss, Wurm1, and Wurm 2. This boundary also coincides with the boundary of the sequence cycles of the sequence stratigraphy. According to the lithofacies analysis of BH4-HN and BH56-ND, the sedimentary cycle of these two boreholes is the cycle of three lithofacies complexes, which are the alluvial facies complex (lower), coastal marsh - lagoon-bay facies complex (middle), and the delta clay silt complex (upper) (Figure 4, Figure 5, Figure 6).

4.2. Characteristics of sedimentary cycles of BH-4HN borehole

Based on the above cycle classification, the stratigraphy of the BH-4HN borehole was subdivided into five cycles, denoted by C_1, C_2, C_3, C_4, and C_5 (Figure 4, Table 2).

The boundaries of the cycles were picked across the incised/eroded surface of the river channels at the depths of 120 m, 105 m, 85 m, 45 m, and 20 m. Each cycle has three lithofacies complexes: regressive alluvial facies complexes; the transgressive coastal swamp and bay-lagoon facies complex; highstand deltaic facies complex. The sedimentary characteristics in the core BH-4HN could identify five alluvial facies complex, five coastal marshy facies complexes, and five coastal facies complex in which consist of bay-lagoon facies and five deltaic facies (Figure 4 and Figure 5).

The five sedimentary cycles correspond to 5 lithofacies complexes that are repeated but evolved by the following rule:

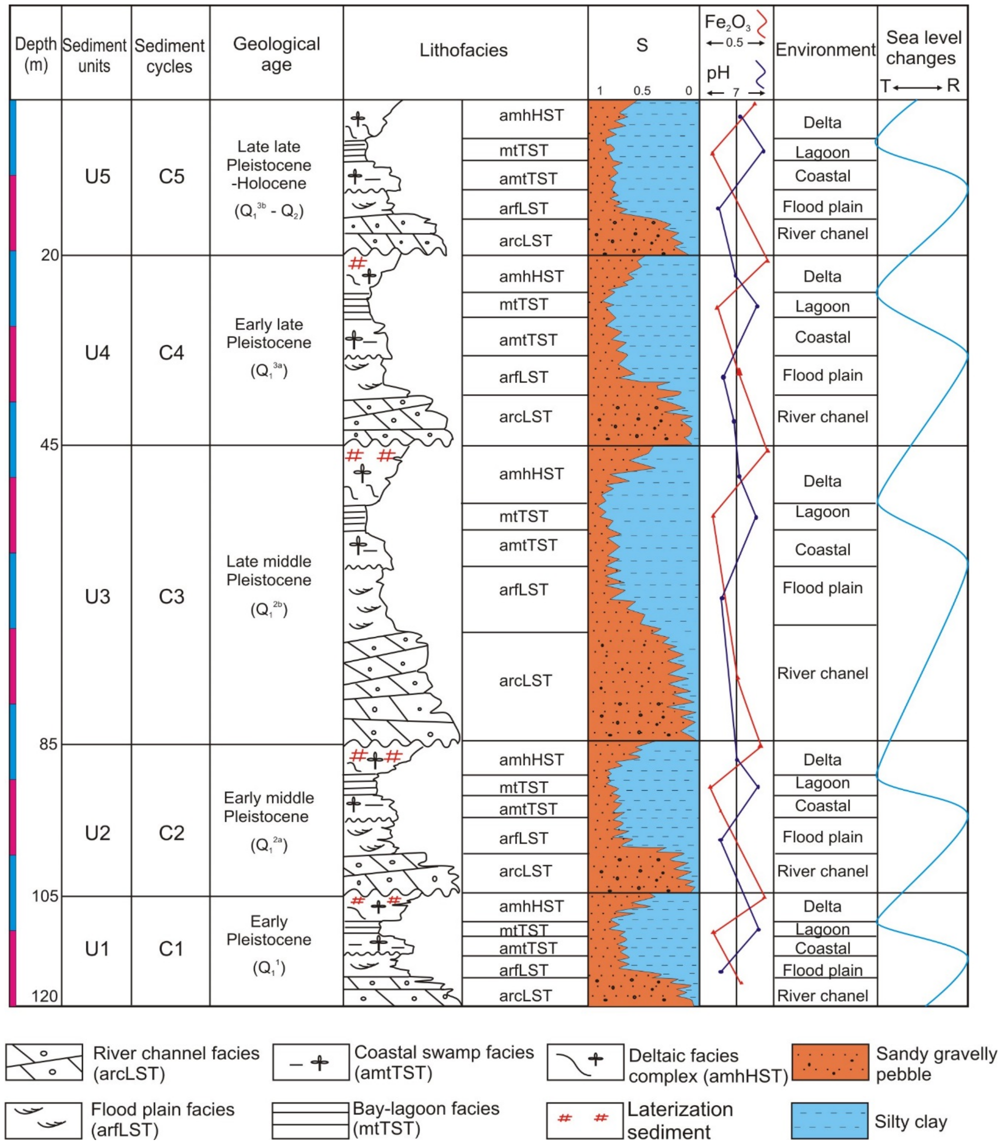

Figure 4. *Variation of the sedimentary parameter of BH-4 HN in cycles at Gia Lam, Ha Noi*

(1) The lowstand alluvial muddy sand facies **($S_m$arLST):**

The general characteristics of the alluvial facies were observed an upward decrease in sediment grain sizes. These are riverbed pebbles and gravels (lower) and flood plain clayey silt facies (upper). From the first cycle to the third cycle, the S index is as follows: (1) C1: S index of the alluvial facies accounted for 100% (BH-4HN and BH56-ND); (2) C2: S index of alluvial facies account for 80%; (3) S index of alluvial facies account for 76-82%; (4) C4: S index of alluvial facies account for 63-65%; (5) C5: S index of alluvial facies account for 62-65%. The debris has a medium to good roundness (Ro = 0.2-0.8), showing that the midland river channel environment had a strong dynamic flow. According to the above mention trend, the lithological composition of river channel sand also varied from polymictic sand (cycles 1, 2, and 3) to oligomictic sand (cycles 4 and 5) (Photo 1).

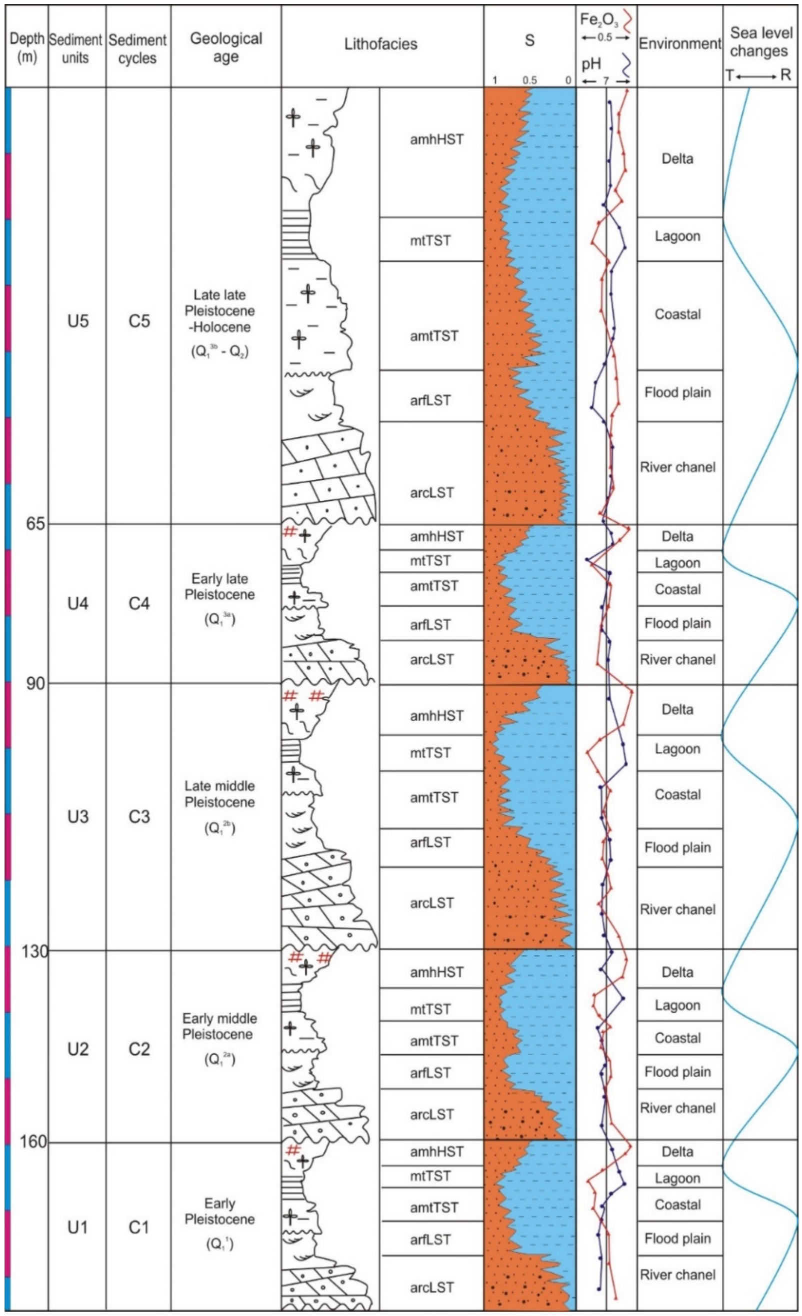

Figure 5. *Variation of the sedimentary parameter of BH-56 ND in cycles at Hai Hau, Nam Dinh*

Table 2. *The average content of granulometric fractions of BH-4HN and BH-56ND*

Sed.	Environment	Lithofacies,	BH-4HN	BH-56ND

Cycles		Sediment systems tract	Pebble & gravel (%)	Sand (%)	Mud (%)	Pebble & Gravel (%)	Sand (%)	Mud (%)
			>2 (mm)	2-0.063 (mm)	<0.063 (mm)	>2 (mm)	2-0.063 (mm)	<0.063 (mm)
C5 Q_1^{3b}-Q_2	Deltaic	$M_s$amhHST	0	27	73	0	45	65
	Coastal	$M_s$amt,Mmt TST	0	22	78	0	18	82
	Alluvial	$S_m$arLST	10	55	35	5	57	38
C4 Q_1^{3a}	Deltaic	$M_s$amhHST	0	29	71	0	25	75
	Coastal	Msamt;Mmt TST	0	25	75	0	21	79
	Alluvial	$S_m$arLST	15	50	35	10	53	37
C3 Q_1^{2b}	Deltaic	$M_s$amhHST	0	40	60	0	33	67
	Coastal	$M_s$amt,MmtTST	0	35	65	0	22	78
	Alluvial	$S_m$arLST	45	37	18	25	51	24
C2 Q_1^{2a}	Deltaic	$M_s$amhHST	0	40	60	0	33	67
	Coastal	$M_s$amt,MmtTST	0	35	65	0	25	75
	Alluvial	$S_m$arLST	35	45	20	23	49	28
C1 Q_1^1	Deltaic	$M_s$amhHST	0	36	64	0	29	71
	Coastal	$M_s$amt,$M_s$mtTST	0	25	75	0	21	79
	Alluvial	$S_m$arLST	25	60	15	12	66	22

Note: $S_m$arLST- Lowstand alluvial muddy sand facies complex; $M_s$amt, $M_s$mtTST-Transgressive coastal mud facies complex; $M_s$amhHST-Highstand sandy mud facies complex

Table 3. *Integration of lithofacies and sedimentary parameters of BH-4HN in Gia Lam, Hanoi.*

Geo. Age	Depth (m)	Sed. cycles	Lithofacies		Kt $(K^+ + N^+)/Ca^{+2}+Mg^{+2})$	So	Ro	Q (%)	S (s/s +m)	pH	Fe_3 $(Fe_2O_3/\Sigma Fe)$
Q_1^{3b}-Q_2	0-20	C5	Highstand deltaic	Sand bar	-	1.3-1.5	0.6-0.8	70-85	0.8-1.0	-	-
				Delta plain	≈1	2.3-2.8	-	-	0.2-0.4	7.1-7.5	0.5-0.7
			Transgressive coastal swamp, lagoon	Lagoon	1.2-1.5	1.5-1.8	-	-	0.2-0.5	7.1-8.5	0.0-0.1
				Coast sawmp	1.0-1.2	1.5-2.8	-	-	0.1-0.3	4.0-7.2	0.0-0.1
			Lowstand alluvial	Flood plain	<0.5	2.5-3.5	-	-	0.2-0.5	6.1-6.7	
				River channel	-		0.2-0.4	35-60	0.7-1.0	-	-
Q_1^{3a}	20-45	C4	Ridge		-	1.3-1.5	0.6-0.8	70-85	0.3-1.0	-	-
			Lagoon		1.2-1.5	1.5-1.8	-	-	0.1-0.4	7.5-7.8	
			Lowstand alluvial		<0.5	2.5-3.5	0.2-0.4	40-60	0.4-1.0	6.4-6.8	
Q_1^{2b}	45-85	C3	Highstand deltaic		≈1.0	1.5-2.5	0.5-0.7	70-85	0.2-1.0	7.1-7.5	

Geo. Age	Depth (m)	Sed. cycles	Lithofacies	Kt $(K^+ + N^+)/Ca^{+2} + Mg^{+2})$	So	Ro	Q (%)	S (s/s +m)	pH	Fe_3 $(Fe_2O_3/\Sigma Fe)$
Q_1^{2a}		C2	Lowstand river channel	-	22.7	0.3-0.6	35-50	0.8-1.0	-	-
Q_1^1		C1	Lowstand river channel	-	2.6	0.4-0.6	35-45	0.7-0.9	-	-

(2) Transgressive coastal swamp sandy mud and bay-lagoon mud facies complex **(Msamt, MmtTST)**

This facies complex is located in the middle of cycles and associated with each other in order upward: coastal swamp mud facies and bay-lagoon facies (marine flooding plain). The fine sediment grain sizes gradually increase and pH slightly increased from 4.0 to 8.5. The sand/mud (S) coefficient also decreased from 0.3 (coastal environment) to 0.1 (bay-lagoon environment) and Eh gradually increased from <0 (coastal marsh environment) to ≥0 (bay-lagoon environment) (Figure 4, Table 1, Table 3).

(3) The highstand deltaic sandy mud facies complex **(MsamhHST)**

The complex of deltaic facies includes 3 lithofacies associated with each other, consisting of prodelta clay facies, delta front sandy mud facies, and delta plain clayey silt facies. In the same direction, the granulometric component increased, the pH index decreased from 7.5 to 7.1, the S index also increased gradually from 0.2 to 1.0 (Figure 4, Table 1, Table 3). Quaternary sediments had been lateriticized due to the activity of groundwater by infiltrated weathering process during regressive phases affected by glacial phase (Figure 4).

4.3. Characteristics of sediment cycles of the borehole BH-56ND

The results of studying all the sediment parameters of granularity, petrophysics, environmental geochemistry of the core sample taken continuously from the core BH-56ND allowed us to identify five sedimentary cycles. The boundaries of these sedimentary cycles were similar to those in the core BH-4HN, which were the eroded surfaces of regressive riverbeds. These surfaces are located at depths of 185 m, 160 m, 130 m, 90 m, and 65 m (Figure 5). Therefore, the thickness of each cycle in this borehole was much larger than that of BH-4HN.

From the upwards, each cycle had three facies complexes, consisting of the alluvial facies complex, the coastal marsh complex, and the gulf, the delta facies complex.

(1) Lowstand alluvial muddy sand facies complex ($S_m$arLST))

The alluvial facies complex had two association lithofacies together: (a) river channel sand facies and clayey silt facies. From C_1 to C_3 cycles in the riverbed, the content of gravelly sand accounted for 0.7-1.0; the softness and roundness were poor (So = 2.5-2.7; Ro = 0.4-0.6) (Table 3), typical for the downstream fluvial environment (Nghi et al. 2016; Nghi et al. 2017). In the C4 and C5 cycles, the pebble content account for 25-45%, while the sand accounted for 25-60% of the roundness and sorting is from poor to moderate (Ro = 0.2-0.7) Table 1, Table 3). The lithological composition of sand also tended to change from polymictic sand (C1 and C2) to oligomictic sand (C4 and C5) (Photo 2).

(2) The complex of coastal marsh facies containing peat and bay-lagoon facies (amt, mt)

This facies complex is covered on the seaward erosion surface of the alluvial facies complex, consisting of three facies: coastal tidal flat sand facies, coastal marshy mud facies that contain peat, and bay-lagoon clay facies. The composition of the fineness of the particles, the pH increased from 7.5 to 7.8, the sand/mud coefficient also decreased from 0.5 (coastal tidal flat environment) to 0.2 (coastal swamp environment) and 0.1 (bay-lagoon environment), and Eh index also increased from <0 (coastal marsh environment) to ≥0 (bay area environment) Table 1, Table 4, Figure 5).

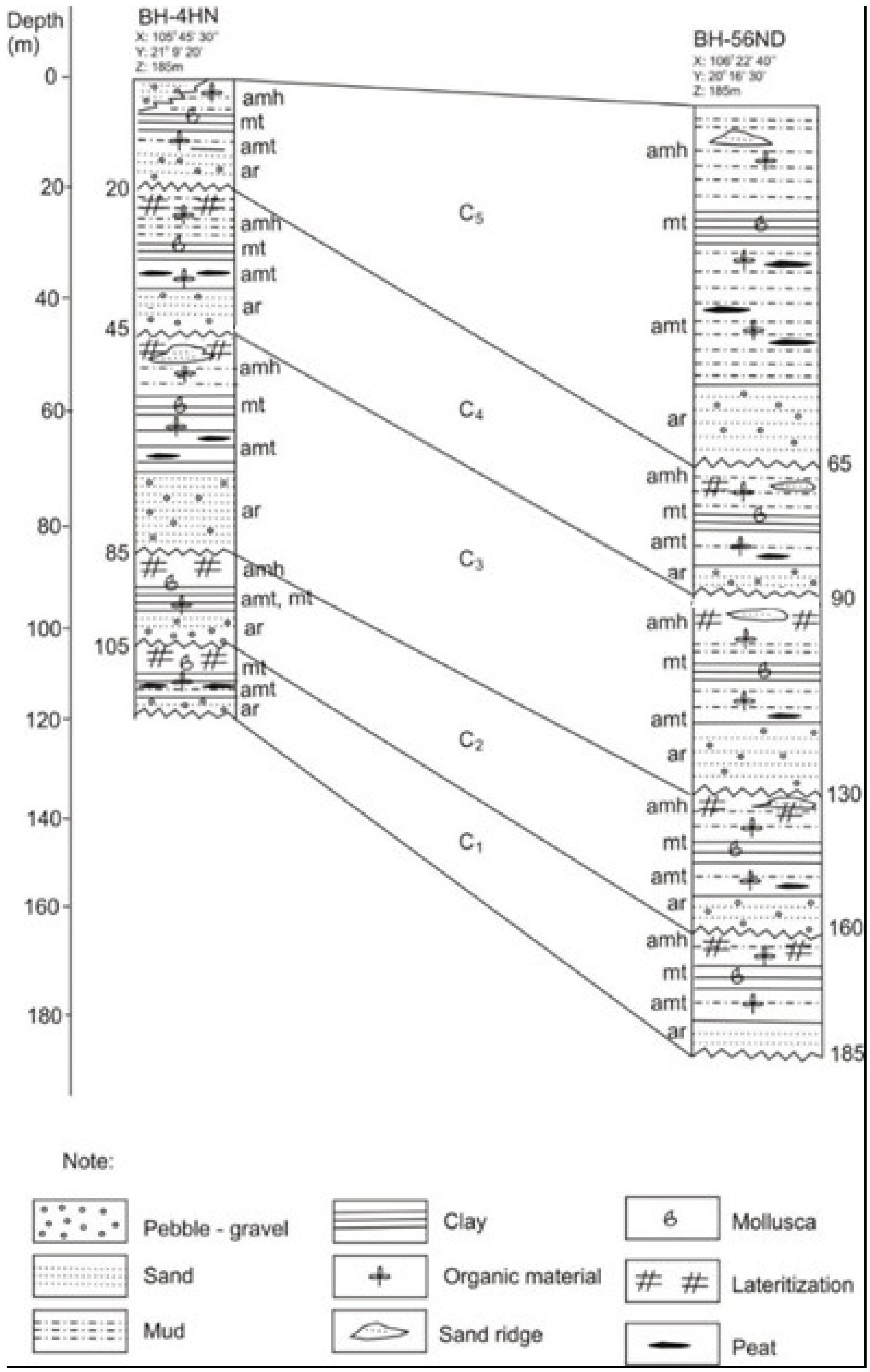

Figure 6. *Diagram correlating five sedimentary cycles of two borehole BH-4HN and BH-56 ND*

(3) Deltaic facies complex (amh).

In the five sedimentary cycles, the delta facies complex consisted of three facies associated with each other as follows: prodelta clay facies, delta front facies, and delta plain facies. In the upward direction, the granularity component increases, the pH decreased from 7.5 to 7.1, the S index (grit + sand/mud) also increased gradually from 0.2 to 0.5 (Figure 5, Table 1, Table 3). Like the core BH-4HN, all delta plains in the borehole BH-56ND were all weathered to become spotted color. In particular, the delta plain of C4 was infiltrated weathered most strongly by the regression of the W2 glaciation that lasted from 50-18ka BP (Figure 3, Photo 1). (Nghi T. 2018).

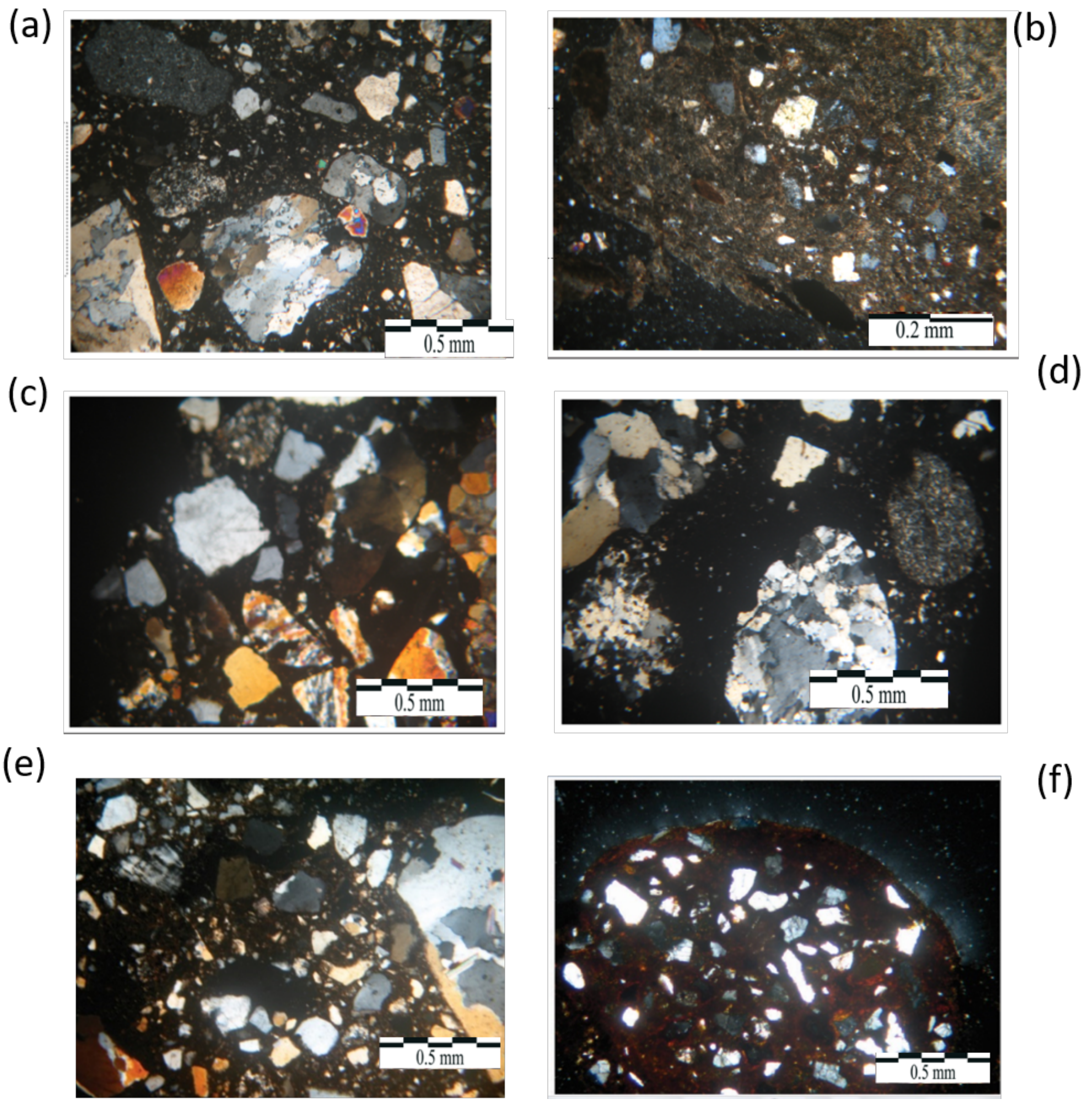

Photo 1. *Photos of thin sections under the polarizing microscope from BH-4HN, Crossed Polarized Light (CPL)*

4.4. Correlation of 5 sedimentary cycles of the 2 boreholes BH4-HN and BH56-ND

Stratigraphic correlations between these two boreholes are presented in Figure 7. Each borehole all has 05 similar sequences corresponding to 05 cycles: Cycle 1: early Pleistocene (Q_1^1); Cycle 2: early middle Pleistocene (Q_1^{2a}); Cycles 3: late middle Pleistocene (Q_1^{2b}); Cycle 4: early-late Pleistocene (Q_1^{3a}) and Cycle 5: late late Pleistocene to Holocene (Q_1^{3b}-Q_2).

It is seen that the thickness of 5 sedimentary cycles tends to increase from the NW (Hanoi – Borehole BH-4HN) to the SE

(Nam Dinh – Borehole BH56-ND), especially the 5th cycle. This change is consistent and well-matched with the development of the Red River Delta toward the open sea. In addition, the southeastward thickening of sedimentary formations may have been triggered by the gradual tectonic subsidence during the Quaternary Period.

It is noteworthy to indicate that the ending of each cycle is marked by yellowish-red mottled clays silt, which was attributed to the influence of the weathering process. This typical color observation suggests that the beginning of next each cycle was affected by weathering process when the whole area was exposed (Figure 6).

(a) Polymictic detritic sand composed of monocrystal quartz (Qm), polycrystal quartz (Qp), poorly sorted and medium rounded of the lowstand systems tract of C_1 (SarLST Q_1^1), at the depth of 119m*;*

(b) Flood plain gray-brown mud facies, poorly sorted of the lowstand systems tract of C1 (MarLST Q_1^1); at the depth of 110m;

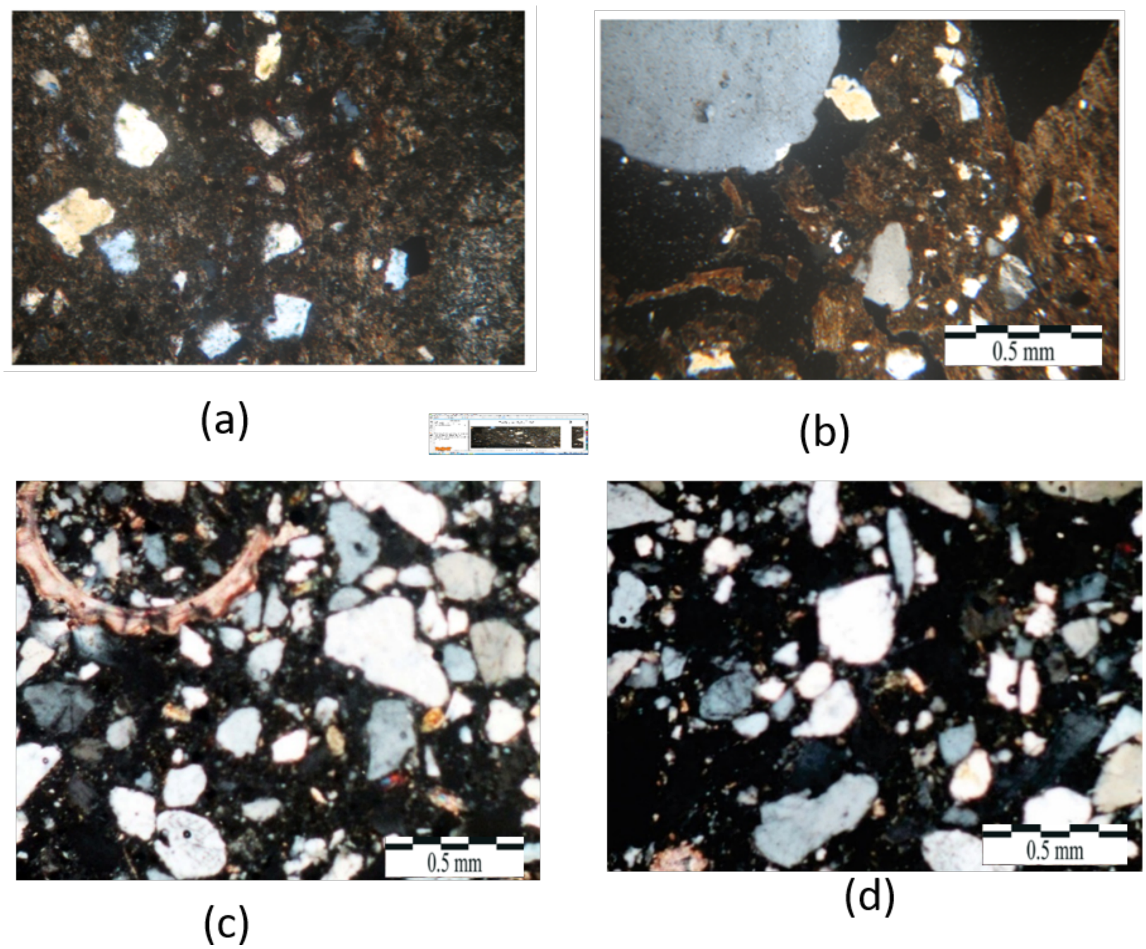

Photo 2. *Photos of thin sections under the polarizing microscope from BH-56ND, Crossed Polarized Light (CPL)*

(c) Polymictic detritic sand composed of monocrystal quartz, polycrystal quartz, poorly sorted and medium rounded of the lowstand systems tract of C_2 (SarLST Q_1^{2a}), at the depth of 103m; (d) Polymictic detritic sand composed of the hydrothermal polycrystal quartz gravel grain, rounded rhyolite fragment, and angular monocrystal quartz, poorly sorted of the lowstand systems tract of C_3 (SarLST Q_1^{2b}), at the depth 80m.

(e) River channel polymictic sandy facies of the fourth cycle of C_4 (SarLSTQ_1^{3a}), poorly sorted, medium rounded, at the depth of 43m.

(f) Lateralization of late Pleistocene deltaic mud sand facies according to highstand systems tract of C_4 ($S_m$amh HSTQ_1^{3a}), at the depth of 23m.

(a) Flood plain gray-brown clayey silt facies, poorly sorted of the lowstand systems tract of C2 (arLST Q_1^{2b}), at the depth of 145m.

(b) Flood plain bearing sand clayey silt facies, poorly sorted of the lowstand systems tract of C3 (arLST Q_1^{2b}), at the depth of 135m.

(c) Tidal flat sand facies of transgressive systems tract of C5 (amt TST Q_2^1), at the depth of 45m. Medium monocrystalline quartz sand baring Mollusca (Mo), well-sorted (So=1.4) and moderate to well rounded (Ro=0.5-0.8).

(d) River channel polymictic sandy facies of late late Pleistocene (arLSTQ_1^{3b}) (C5), at the depth of 60m.

Table 4. *Integration of lithofacies and sedimentary parameters of BH-56ND in Hai Hau, Nam Dinh.*

Geo. age	Depth (m)	Sed. cycles	Lithofacies		Kt	So	Ro	Q (%)	S	pH	Fe_3 (Fe_2O_3/ΣFe)
Q_1^{3b}-Q_2	0-65	C_5	Highstand deltaic	Sand bar	-	1.2-1.3	0.6-0.9	75-90	0.8-1.0	-	
				Delta Plain	≈1.0	2.3-2.5	-	-	0.1-0.4	7.2-7.8	0.5-0.7
			Trans. Transition	Bay	1.2-1.5	1.5-3.0	-	-	0.1-0.3	7.1-8.5	0.0-0.2
				Coast sawmp	1.0-1.2	1.5-3.0	-	-	0.1-0.3	7.1-8.5	0.0-0.1
			Lowstand Alluvial	Flood Plain	<0.5	2.5-3.5	-	35-60	0.3-0.5	-	-
				River channel	-		0.2-0.4		0.8-1.0		-
Q_1^{3a}	65-90	C_4	Highstand Deltaic	Sandridge	-	1.3-1.5	0.6-0.8	70-85	0.8-1.0	-	-
				Delta plain	≈1.0		-	-	0.2-0.5	7.1-7.3	0.8-0.9
			Lagoon		12-1.5	1.5-1.8	-	-	0.1-0.3	7.2-7.8	0.0-0.2
			Lowstand alluvial	Flood Plain	<0.5	2.5-3.5	-	-	0.2-0.5	6.4-6.8	-
				River channel	-	1.9-2.5	0.2-0.4	40-60	0.7-1.0	-	-
Q_1^{2b}	90-130	C_3	Highstand deltaic		≈1.0	1.5-2.5	0.5-0.7	70-85	0.2-1.0	7.1-7.5	0.7-0.8
			Lagoon		1.2-1.5	1.5-1.8	-	-	0.1-0.3	7.2-7.5	0.0-0.1
			Lowstand alluvial	Flood plain	<0.5	2.5-3.5	-	-	0.2-0.4	6.1-6.5	-
				River channel	-	1.9-2.5	0.3-0.5	35-50	0.8-1.0		-
Q_1^{2a}	130-160	C_2	Highstand Deltaic	S.ridge	-	1.3-1.5	0.4-0.6	60-75	0.7-1.0	-	-
				Delta	≈1.0				0.2-0.5		0.6-

Geo. age	Depth (m)	Sed. cycles	Lithofacies		Kt	So	Ro	Q (%)	S	pH	Fe_3 (Fe_2O_3/ΣFe)
				plain							0.8
			Transgressive coastal Swamp, lagoon	Lagoon	1.2-1.5	1.8-2.8	-	-	0.2-0.5	7.1-7.5	0.0-0.1
				Coastal Sawmp	1.0-1.2				0.1-0.3		0.0-0.1-
			Lowstand alluvial	Flood plain	<0.5	2.5-3.5	-	-	0.1-0.3	6.1-6.5	-
				River channel	-	1.9-2.5	0.1-0.4	35-50	0.7-1.0	-	-
Q_1^1	160-185	C_1	Highstand Deltaic	Sandridge	-	1.5-2.5	0.4-0.6	45-60	0.8-1.0		-
				Delta plain	≈1.0				0.2-0.5	6.9-7.2	0.5-0.7
			Transgressive coastal Swamp, lagoon	Lagoon	1.2-1.5	1.8-2.5	-	35-50	0.0-0.3	7.1-7.5	0.0-0.2
				Coastal Swamp	1.0-1.2	2.3-2.8	-	-	0.2-0.5	4-7.2	0.0-0.1
			Lowstand Alluvial	Flood Plain	<0.5	2.5-3.5	0.1-0.4		0.2-0.6	6.1.-6.5	-
				River channel	-	2.5-2.8	0.2-0.4		0.8-1.0		-

5. Discussion

The comparison of 2 boreholes BH4-HN and BH56-ND can allow drawing the following comments of the similarities and differences:

- *Similar characteristics*:

1) Both two boreholes have 5 cycles about the 5 cycles of the global sea-level change. Each sedimentary cycle corresponds to a sequence.

2) Each sequence includes 3 facies complexes: (1) Lowstand alluvial sand and gravel facies ($S_g$arLST); (2) Complex of coastal facies and maximum marine flooding plains ($M_s$amt;mtTST); (3) Highstand deltaic sandy mud facies complex ($M_s$amhHST).

- *Different characteristics*:

1) For borehole BH4-HN, the sediment thickness of the cycles tends to decrease gradually from Pleistocene to Holocene, while borehole BH56-ND varies oppositely: (1) During Pleistocene period cycles of C2, C3 and C4 have a similar thickness to these 3 cycles in borehole BH4-HN. However, by the C5 cycle, the BH56-ND borehole has a thickness of 56m, a sudden increase compared to 30m in the borehole BH4-HN. That in the Pleistocene on the entire plain, tectonic subsidence occurred with uniform amplitude, until the end of the late Pleistocene to the Holocene in the Nam Dinh area, i.e. lower downstream, the subsidence amplitude was more than in the Hanoi area, i.e. the midland downstream of the Red River Delta.

2) The lower part of the C1, C2, and C3 cycles in the Hanoi area is characterized by the midland riverbed coarse sandy gravel facies complex, while the Nam Dinh area is characterized by the downstream riverbed sand facies complex. That proves that there is a change in the tectonic setting and topography between the two areas mentioned above, which has caused the boundary of the sedimentary facies to change accordingly in space.

6. Conclusions

1. Based on the detailed study of material composition and lithofacies analysis from core samples of 2 boreholes BH-4HN and BH-56ND, could the author identify five cycles of sedimentary, corresponding to five

global sea-level change cycles:

C1 period aged from 1600-700 ka BP, corresponding to early Pleistocene (Q_1^1) due to the influence of the glacial/interglacial cycle Gunz/G-M;

The C2 cycle aged between 700-150 ka BP, corresponding to the early middle Pleistocene (Q_1^{2a}) due to the influence of the glacial/interglacial cycle Mindel/M-R;

C3 cycle aged between 150-70 ka BP, corresponding to the late middle Pleistocene (Q_1^{2b}) due to the influence of the glacial/interglacial Riss/R-W1;

C4 cycle aged from 70 to 30 ka BP, corresponding to the early late Pleistocene (Q_1^{3a}) due to the influence of the glacial/interglacial cycle Würm1/W1-W2

The C5 cycle aged from 30 ka BP up to now, corresponding to late late Pleistocene to Holocene (Q_1^{3b}-Q_2) due to the influence of the Würm2 glacial cycle and the Holocene transgression.

In the Quaternary stratigraphy, the three complexes of lithofacies had characteristics like 3 marking layers of each cycle: (1) pebble facies are the signs to identify the unconformity boundary of incised erosion of river bed; (2) grey-greenish clay facies are the signs of maximum transgressive phase; and (3) yellow-red spotted clayey silt is a sign of the period which the deltaic plain sediment was weathered by groundwater infiltration.

4. Quaternary sediment cycles and sequences were reliable to study geological mapping and mineral resources potential assessment, especially groundwater. River-bed sandy gravelly pebble facies belonging to lowstand systems tract are high-quality aquifers. At the same time, the grey-greenish clay in the bay lagoon was a very good aquifuge layer.

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