QUATERNARY GEOLOGICAL MAP OF THE CONTINENTAL SHELF OF VIETNAM AT THE SCALE OF 1:1,000,000

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ABSTRACT. Eastern Sea of Vietnam is the world's largest semi-open sea and is bounded by archipelagos, islands, mainland and connected partially with Pacific and Indian Ocean. Its total water surface area is about 2,974,600km^2. Vietnamese and foreign geoscientists have researched, got samples and mapped the geological map of Eastern Sea since 1960s but no guidance or right method was carried out to map, especially in presenting geological units on geological map. So that, in this article, the Geological Quaternary map of Eastern Sea is created by using group of methods, methodology and literatures for sediment, geophysics,... The methodology is systematization of research results of Vietnamese and foreign scientists on Quaternary geology in mainland and continental shelf. One of those results is the classification of sedimentary cycles in relation to sea level change in Quaternary. In seabed of Eastern Sea, there are 25 geological units of 7 sedimentary cycles, which includes 4 lithofacies Pliocene - Quaternary, 14 lithofacies in Pleistocene and 6 lithofacies in Holocene, coral reefs and volcanic rocks. Especially, there are 8 ancient shoreline zones that acted as geological boundary from 3500m to 25m water depth in the sea bottom.

1. Introduction

Vietnam, situated in South East Asia, has a long coast of about 3260km and more than 1 million square kilometers of water surface. It is rich in minerals, such as oil, gas, placer mineral, etc. In the recent decades, the reinforcement of marine investigation and sampling on the Vietnamese sea floor have released by Vietnamese and foreign, such as French, German and Japanese, scientists. But up to now, a guidance norm for Pliocene - Quaternary marine mapping is still unavailable in Vietnam.

For mapping Pliocene - Quaternary geological map of continental shelf at the scale of 1:1,000,000 the authors based on data assemblage and consolidation on geophysics and geology with group of methods and methodology such as geophysical methods, methods for studying material compositions.

2. Methodology and methods

2.1. Methodology and principle of mapping geological quaternary map

In order to compile the map of Quaternary formation of the Vietnamese Eastern

Sea and its adjacent areas, the authors have applied the systematic approach with two fundamental contents that are Quaternary Stratigraphical Division and mapping methods. It is established by the age and genesis of the sediment. This principle reflects changes of lithofacies, paleomicrofossil, hydrodynamic, geochemical environment, transportation, depositional environments, distribution of erosion and weathering regions, etc. It is necessary to clarify the relationship between sediment composition, sea level change and tectonic movement.

Table 1. Stratigraphical boundaries in Quaternary

Era	System	Epoch	Stage	Sub-stage	symbols	Numeric Ages		Origins
Cenozoic	Quaternary	Holocene	Upper		Q_2^3	3000		m, mb, am
			Middle		Q_2^2	7000	R_1	am, m, ms, mb
			Lower		Q_2^1	10000	R_2	
		Pleistocene	Upper	Upper	Q_1^{3b}	70000	R_3	
				Lower	Q_1^{3a}	125000	R_4	am, m
			Middle		Q_1^2	700000	R_5	m, am , a
			Lower		Q_1^1	1600000	R_6	m, am , a
	Neogene	Pliocene			N_2	5000000		mD, m, mT

Note: N_2: Pliocene, Q_1^1: Early Pleistocene; Q_1^2: Middle Pleistocene; Q_1^{3a}: early part of Late Pleistocene; Q_1^{3b}: late part of Late Pleistocene; Q_2^1: Early Holocene; Q_2^2: Middle Holocene; Q_2^3: Late Holocene; a: alluvial; am: deltaic; m: marine; ms: coastal sandy bar; mb: coastal marsh; mT: turbidite; mD: submarine deluvium.

Global sea-level change during the Quaternary is the direct reason for tectonic movement and geological structures are the reason so far for sedimentary composition. Both two reasons have been happening simultaneously and have cyclicity (phase). The beginning of the basic sedimentary cycle was marked by relatively coarse sediment (pebbles, gravels, coarse sands,...), which reflects vertical differentiation of relief,

caused by strong tectonic movement in the uplift eroded area (marginal plains, coastal mountain area), forming fluvial and marine terraces. Conversely, in the central part of the Cenozoic basins (such as the Red River rift, the Mekong river rift, the South Con Son rift, the Phu Khanh rift,...), and in the subsided monocline continental shelf such as the South Central part of Vietnam, subsidence had occurred periodically (cyclicIty) for whole basins both on the land and in the ocean area. Therefore, the coarse layer in the lower part of the cycle reflects strong energy of currents, tectonic uplifting movement in the marginal area was overwhelming subsidence in the basins. Synchronously to glacial is a global marine regression, that caused continent widen and marine flooded areas were reduced and proluvial, alluvial sediments were dominated.

When global transgression occurred, climate was warmed up, the energy of the continental flow was reduced, chemical weathering was stronger than physical one. This is the reason to explain why the fine sediments (clays and chemical-biological sediments) have more products of chemical weathering than mechanical materials. Boundary of each cycle corresponds to maximum transgression.

The sedimentary succession of Eastern Sea in Early Pleistocene - Holocene are divided into 6 sedimentary cycles corresponding to 6 phases of sea level change in Quaternary. Each of sedimentary cycle is characterized by upward fining rule. It means that a depositional cycle is began by coarsest sediments of continental environment and ended by finest sediments in stratification of marine, lagoon or bay and sediment is fining upward from early to late of each cycle. These sediment layers reflect the sedimentary evidences of regression and transgression phase as well as evidences of highstand and lowstand system tracts. These deposits have different textures: progradational dowlaps in lowstand system tract, aggradational onlap, and toplap in highstand system tract. They are proved by appearance of sandy bars, sandy ridges in continental shelf and river mouth bars in Red River and Mekong River.

The principle for mapping Quaternary formations in the continental shelf is that geological units are established by overlapping stratigraphic units together in vertical direction and each of geological units is painted by a special color. Therefore, the geological map of Eastern Sea is presented more usefully and could be used as a basic sea bottom map.

2.2. Methods

In this articles we also use a group of methods for studying material compositions and lithological parameter such as: sorting coefficient (So), median size (Md), skewness (Sk) from grain-sized analysis, roundness (Ro), sphericity (Sf) from analysis of morphology of clastic particles, analysis of minerals, composition of SiO_2, FeO, Fe_2O_3, CaO, Na_2O, K_2O, MgO, environmental chemical index,...

The selection of scale of the map is very important for interpretation and performance of geological formation on the map. Stratigraphical boundaries in Quaternary are divided by comparison the sedimentary cycles and sea level change (Table 1).

3. Stratigraphy and sedimentary cycles

In the Vietnamese Eastern Sea, 25 units of sediments belonging to 7 sedimentary cycles have been identified and they have a close relation to 7 ancient shoreline zones, including Pliocene. These cycles have been mapped as 7 geological members. In general, the ancient shorelines coincided with the geological boundaries. Two particular formations concerning with volcano and coral are classified and described separately.

In Pliocene - Quaternary this area is covered by turbidities muddy, volcanic ash, volcanic bomb facies; turbidities sand, sand mixed volcanic mud facies; deep sea volcanic mud facies; Paleo marine clayish mud, sandy silt facies and paleo fans gravel, gravelly sand, muddy sand facies. They appear at the depth from -3000m to -3500m and on the outer margin. The provenance of them are mainly from terrigenous materials carried out from paleoriver with fragments and volcanic mud. Their common feature is weakly cemented, distributing in the form of fans shape in continental slope rise with gentle or horizontal layers with thickness from tens meters (in the marginal areas or in uplifted block) to thousands meters (in basins). In marginal shelf, the Pliocene deposits formed as deltaic wedges.

There are 6 sedimentary cycles in Early Pleistocene to Late Holocene, which are:

- The first sedimentary cycle: Early Pleistocene composed of paleo fans gravel, gravelly sand, muddy sand facies in the early of the cycles and ended by paleo marine clayish mud, sandy silt facies (Tran Nghi, 1991a, 1991b, 1992).

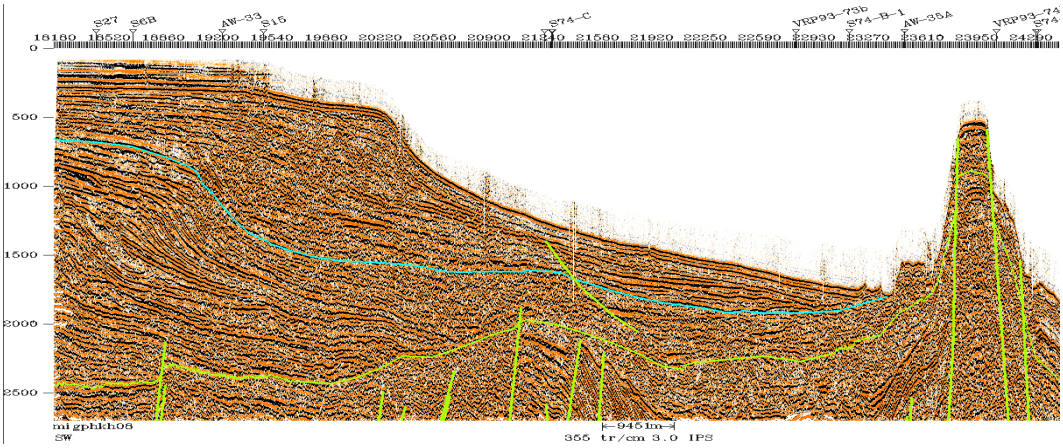

Figure 1. Deltaic progradation sediment in the age of N_2-Q_1^1 in Central continental of Vietnam (line SVOR-93-110)

- The second sedimentary cycle: Lowermost Middle Pleistocene composed of paleo fans sand, gravelly sand, muddy sand facies in starting of cycles which corresponding to regression phase and paleo shallow marine sand, silty sand, clayish mud facies in the ending which formed in transgression phase.

- The third sedimentary cycle: Uppermost Middle Pleistocene was lined by paleo fans gravelly sand, muddy sand facies and covered by paleo shallow marine sand, silty sand, clayish mud facies. Firstly, this cycle was effected by regression phase what corresponding to Riss glaciation and then it was effected by interglaciation R - W1 phase.

- The fourth sedimentary cycle Lowermost Late Pleistocene was characterized by two main sedimentary facies which are: Paleo fans gravelly sand - silt - clay facies formed in regression phase corresponding to Wurm1 glaciation (W1) in the starting and ended by paleo shallow marine clayish muddy silty sand facies in interglaciation W1 - W2 phase.

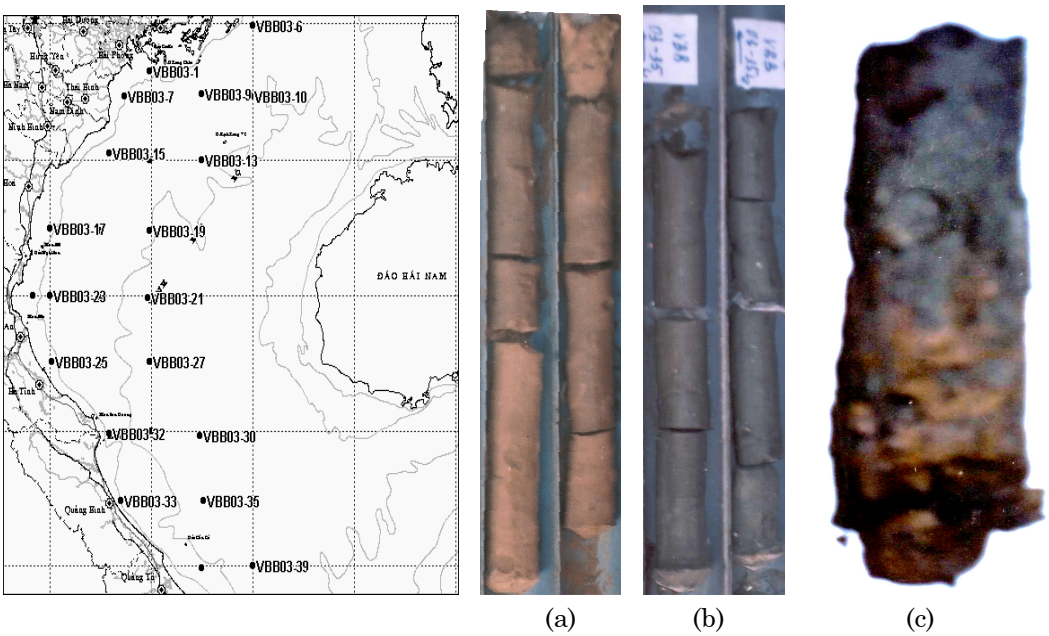

Figure 2. (a) - Silty clay of modern deltaic sediment (amQ_2^3) in Gulf of Tonkin in VBB03-7, (b) - green grey clay mud of bay (mQ_1^{3b}-$_2^1$) in VBB03-35 and (c) - spotted clay marine (mQ_1^{3a}) in VBB03-21.

- The fifth sedimentary cycle: Uppermost Late Pleistocene - Early Holocene and Early - Middle Holocene included 5 sedimentary facies that formed in Regression phase corresponding to Wurm 2 glaciation (W2) and the first Flandrian trangression phase. The paleo river channel sand - silt - clay mixed gravel facies associated with paleo fans sand - silt - clay facies in timing in Wurm 2 glaciation. The paleo lagoonal clayish mud facies; paleo shallow marine clayish muddy sand facies; paleo tidal flat sand, gravelly sand facies are formed and associated together in the first Flandrian transgression phase. From Early to Middle Holocene, sedimentary formation was started by Paleo

lagoonal clayish mud, peat facies; Paleo shallow sea clayish mud, silty sand facies; Paleo sandy bars sand, gravelly sand facies associated together by timing in Flandrian trangression phase.

- The sixth sedimentary cycle was in age of Late Holocene and was characterized by sedimentary facies of regression after Flandrian and modern transgression phase such as: Bay mud facies; Shallow sea muddy sand facies; Lagoonal clayish mud, peat facies; Delta front silty sand, clayish silt facies. These facies were associated and transited by timing from Lowermost to Uppermost of Late Holocene.

Beside that, there are many coral reefs developed along the littoral zone at different times, especially Holocene corals. The typical ones located in the Gulf of Tonkin, near shore of Central Vietnam, in the Paracel and Spratley. The coral reef in littoral zone was developed from Middle to Late Pleistocene to Middle Holocene (Flandrian transgression). The following stage of each phase corresponds with the regression that produced erosive corals and karstic relief. During the Late Holocene regression, another coral platform was produced at recent depth of 2-3 meters. The active transgression has produced coral platform and wave-cut bench. The corals of Paracel and Spratley Corals had a large atoll forms with hermatype. This hermatypic coral possessed an elliptical shape and was classified into two classes. The corals of two archipelagos showed well their growth up, development and perish in accordance with the rhythmic features and cyclicity.

The strong tectonic activities in this area were controlled by the Philippine and Indonesian subduction zones, transform faults, axis of spreading ridges. Therefore, the volcanic activities were also strong. Along the Vietnamese coast from 0 to 200 meters deep, there are many basalt formations, some of them were exposed near shore such as Con Co island, offshore from Quang Nam to Quang Ngai provinces and south east to south of the Vietnamese continental shelf and in the abyssal with the depth over 200 meters. The Eastern Sea abyssal is the place where the oceanic crust exposed in the form of triangular shape with the right line oriented NE-SW and the bottom line expanded to the Philippine archipelago. On the seafloor of this area, it was observable the existence of volcanic structures aligned with fault systems or post-rifted fans and is coved by a thin sediment layer.

In continental shelf of Vietnam Eastern Sea still remains river channel system, which formed in regression phases and composed of river channel well sorted and rounded gravel, sandy gravel and coarse sand.

The ancient shorelines system or more precisely the shoreline zones are the most important Quaternary geological events. They are scientific foundations and geological records during Quaternary time. They manifested throughout the wave-cut niches, abrasion terrace, coastal sandy platforms and sandy bars in the central part of Vietnam, the sandy bodies in the Cuu Long Delta as well as Red River Delta that

marked the highstand and lowstand water level during the transgression and regression respectively.

On the seabed of the Vietnamese continental shelf and adjacent area, eight shoreline zones (including 7 shoreline zones in Quaternary and 1 in Piocene) with various ages, located at different depth, have been identified as following (Hutchison, 1989; Chen et al., 1993):

1. A shoreline with Pliocene age, corresponding to Dunai glacial period, located at the depth between 3000 and 3500 meters (N_2).

2. A shoreline with Early Pleistocene age, corresponding to Gunz glacial period, located at the depth between 2000 and 2500 meters (Q_1^1).

3. A shoreline with Middle Pleistocene age, corresponding to Mindel glacial period, located at the depth between 1000 and 1500 meters (Q_1^{2a}).

4. A shoreline with Lowermost Middle Pleistocene age, corresponding to Riss glacial period, located at the depth between 400 and 500 meters (Q_1^{2b}).

5. A shoreline with Late Pleistocene age, corresponding to Wurm I glacial period, located at the depth between 200 and 300 meters (Q_1^{3a}).

6. A shoreline with Uppermost Late Pleistocene age, corresponding to Wurm II glacial period, located at the depth between 100 and 120 meters (Q_1^{3b}).

7. A shoreline with Late Pleistocene - Early Holocene age, corresponding to the first highstand water level during the Flandrian transgression, located at the depth between 50 and 60 meters (Q_1^{3b} - Q_2^{1-2}).

8. A shoreline with Early - Middle Holocene age, corresponding to the second highstand water level during the Flandrian transgression, located at the depth between 25 and 30 meters (Q_2^{1-2}).

4. Conclusion

In Pliocene - Quaternary, Vietnam Eastern Sea is established and characterized by 25 lithofacies corresponding to 8 ancient shoreline zones in Quaternary - Pliocene. Besides, as for two particular formations concerning with the volcano and coral are classified and described separately.

The ancient shorelines system or more precisely the shoreline zones are the most important Quaternary geological events. They manifested throughout the wave-cut niches, abrasion terrace, coastal sandy platforms and sandy bars in the central part of Vietnam, the sandy bodies in the Cuu Long Delta as well as Red River Delta that marked the highstand and lowstand water level during the transgression and regression respectively.

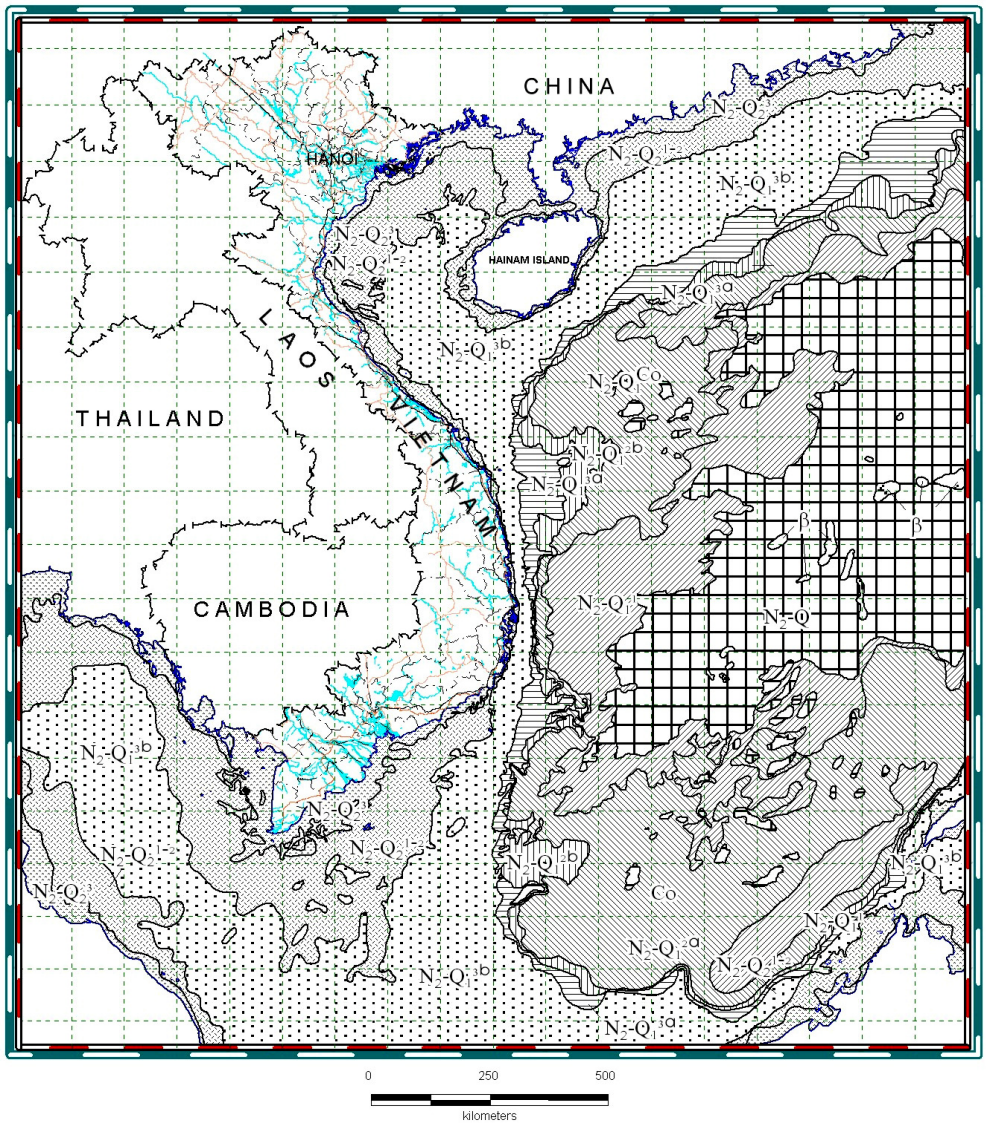

Figure 3. Map of Quaternary Geology of continental shelf of Vietnam

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