

Initial understanding and assessment of role of oceanographic features for ferromanganese crusts and nodules in the East Vietnam Sea

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Abstract

The iron and manganese content in marine water is very small but the volume of ferromanganese nodules contributes 30% of the total mass of polymetallic nodules and crusts in marine and ocean floor. This suggests that the process of enrichment of ferromanganese crusts and nodules is not only contributed by chemical processes but also by oceanographical and biological processes. The article indicates the initial results of analyzing oceanographic, biological, and environmental features to understand their roles in the growing ferromanganese crusts and nodules and to predict the distribution of ferromanganese crusts and nodules in the East Vietnam Sea. As a result, ferromanganese crusts and nodules in the East Vietnam Sea can be distributed in the continental slopes, where upwelling and downwelling currents occur, to ensure enough dissolved oxygen concentration for the enrichment of ferromanganese crusts and nodules as well as to meet required conditions for microbial activity, which is involved in these processes. However, due to the limitations of the results of studying the enrichment of ferromanganese crusts and nodules in the East Vietnam Sea, the paper just shows the prediction of the distribution of ferromanganese crusts and nodules. Thus, it is necessary to carry out the expedition for enrichment processes of ferromanganese crusts and nodules and to determine the factors that impacted the growing ferromanganese crusts and nodules in the East Vietnam Sea.

Keywords: East Vietnam Sea, Fe-Mn, oceanographic.

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INTRODUCTION

Ferromanganese crusts and nodules (Fe-Mn) are formed on the slopes of seamount ranges and the seabed surface. The rate of formation and development of Fe-Mn crust is about 1–5 mm/million years [1]. The thickness of this crust can reach 25 cm with a cumulative time of about 80 million years found in the Central Pacific region [1, 2]. Typically, the Fe-Mn crusts and nodules are found on the surface of deep valleys with depths of around 3,500–6,500 m [3] or the slopes of seamounts/submarine ridge at depths of around 1,500–2,000 m [1, 4]. Most Fe-Mn nodule studies and exploration mainly focus on the Equatorial Pacific regions [3], secondarily conducted in the Atlantic and Indian Oceans [5, 6]. In other marine areas, there are few research results on the existence of Fe-Mn crusts and nodules.

The East Vietnam Sea with an area of over 1 million km² contains several mineral resources, such as titan and iron in coastal waters of Ha Tinh, the reserves of 23.68 million tons of ilmenite and zircon ore in offshore places; and pyrite ore in the shelf, bathyal and abyssal regions and mainly at the edge of the continental shelf to the continental rise with a depth of 200–2,800 m. Fe-Mn nodule has been discovered in Truong Sa archipelago with an average content of 1.5% and the concentration increases gradually to a depth of 500–3,000 m. Fe-Mn nodules are also formed and accumulated in several places in the East Vietnam Sea [7-9]. Zhong et al., [7] reported that Fe-Mn crusts and nodules were found in the slopes and continental shelves of the the East Vietnam Sea at depths from 400 m (in the north of the East Vietnam Sea) to 3,500 m (in the bathyal and abyssal regions in the north and center of the East Vietnam Sea). Thus, Fe-Mn crusts and nodules could contribute from shallow waters to continental shelves and the oceans. However, so far we have not been able to assess the distribution and reserves of Fe-Mn crusts and nodules due to the lack of foundation data.

Therefore, based on the principle of Fe-Mn nodule formation and the law of distribution of

forming conditions related to chemical and biological processes, this paper presents the construction of a scientific basis for prediction of Fe-Mn nodule distribution areas in the East Vietnam Sea in general and in the bathyal and abyssal regions of southwestern East Vietnam Sea in particular.

CONDITIONS FOR FORMATION OF Fe-Mn CRUSTS AND NODULES IN THE SEA AND OCEAN

Fe-Mn crusts and nodules, known as precipitates of iron/manganese hydroxide, exist in two forms: (1) the nodule types in spherical or oval shape lying sporadically on the seafloor or agglomerating into “pebble” and “gravel” blocks distributed on the floor of bathyal and abyssal regions; and (2) the crust types covering seamount slopes in the deep sea.

These crusts often accumulate at the depths from 400 m to 7,000 m [2], in non-sedimentary areas located between active or inactive volcanoes/seamount and on the abyssal plain in the ocean. The thickness of the crust may be in the range of some millimeters to 250 mm. The Fe-Mn nodules are enriched by the impact of the upwelling and disturbance of water bodies on the erosion of the seamount slopes. At the seamount slopes, there is the enhancement of the water interaction between the oxygen-rich bottom zone and the upper oxygen-minimum zone with a nutrient-rich zone. In the seawater, Mn and Fe concentration is very low (about 0.0004 ppm), but they can account for more than 30% of the total multi-metal nodule mass [10]. These nodules grow very slowly (few millimeters per million years) by precipitation of iron and manganese hydroxide colloids around solid-cells in a motion state under the condition of the bottom current causing the oscillation of the water layer close to the bottom sediment. The nodules can grow to the extent that a dense layer covered the seabed surface of large areas. The accumulation of Fe-Mn nodules often occurs on the floor of deep-sea with an oxygen-rich zone. However, in shallow waters, the oxygen-poor bottom zone can also cause an accumulation of Fe-Mn and other metal nodules (figure 1). The Fe-Mn nodules have a large specific surface area with

two opposite colloids, a cation of iron colloids and an anion of manganese colloids. As the result, the rigid association of two colloids exists in a nodule (figure 1).

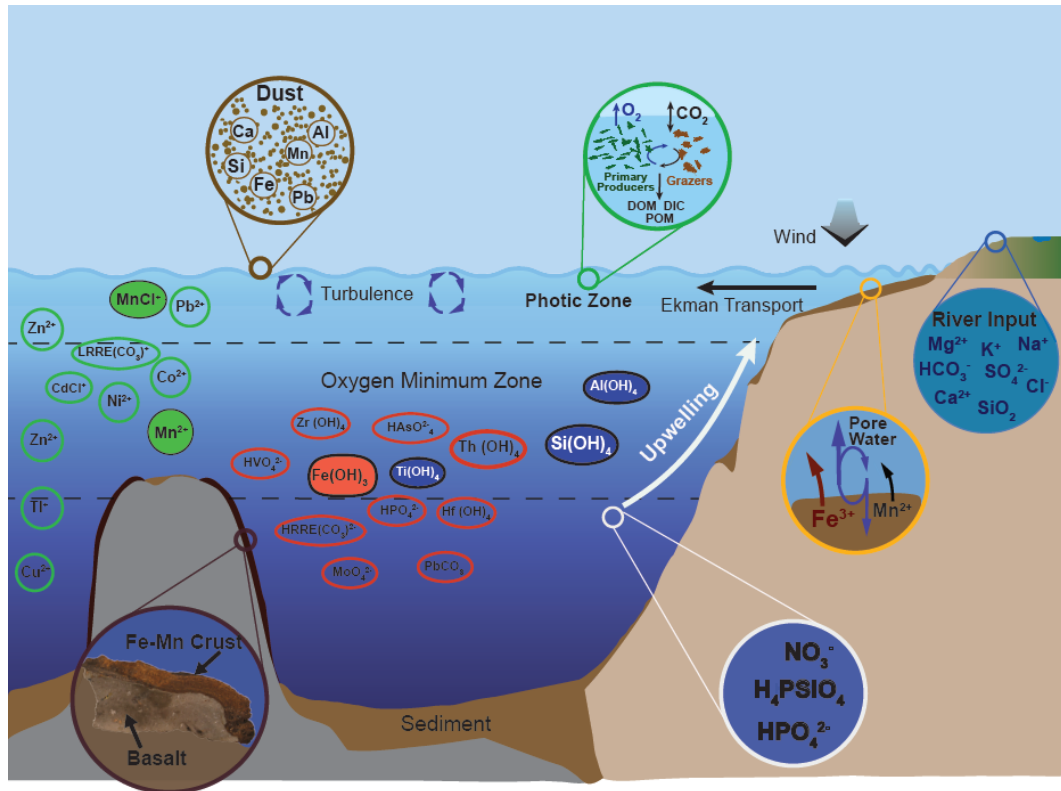
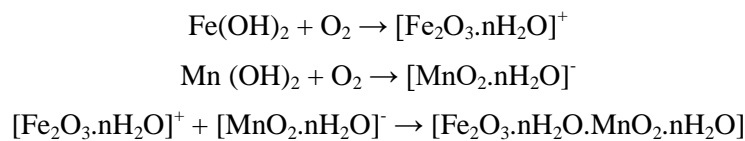
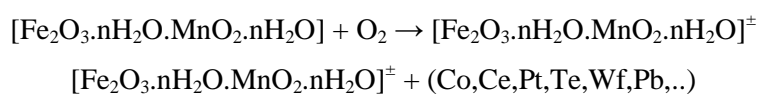


Figure 1. The model link source points and influences on the formation of Fe-Mn crusts and nodules on the continental shelf [14]. DOM: Dissolved Organic Matter, DIC: Dissolved Inorganic Carbon, POM: Particulate Organic Matter

The process of forming Fe-Mn nodule begins from iron (II) hydroxide and manganese (II) hydroxide of hydrothermal eruption, and then they oxidized to iron (III) colloid and manganese (IV) colloid:



The subsequent oxidation process at the surface of Mn and Fe oxygen-hydroxide colloid promotes metal accumulation and retention of sensitive metal with redox conditions (e.g. Co, Ce, Pt, Te, Tl) [4, 11]. Notably, the concentration of some rare earth elements, such as Wf, Pb, Co, Mn, Te and Pt, in the crusts is many times higher than their concentrations in seawater [2, 4]:



The basic principles of geochemical and oceanographic processes of the formation of Fe-Mn crust and other metal accumulation are the scientific basis for forecasting potential formations of Fe-Mn crust and nodules [3]. Submarine volcanoes are the most potential environment for metals to accumulate on the seamount slopes with depths ranging from hundreds to thousands of meters. Thousands of undiscovered seamounts are distributed from the Atlantic Ocean (off South Africa) to the central Pacific Ocean. The thickest and oldest Fe-Mn crust in the world in general and in the Pacific region in particular takes 80 million years to form. The lithospheric sediments in the equatorial waters of the Pacific Northwest are known to be the oldest with many seamount ranges, therefore, the Fe-Mn crusts and nodules are the most abundant. The potential for Fe-Mn crusts and nodules in the Atlantic Ocean has been limitedly studied although they are commonly distributed in the area [12]. Recently, the potential for Fe-Mn crusts and nodules in the polar region was also discovered [13]. In

general, most of the Fe-Mn crust and nodule areas are usually identified in large oceans with numerous seamount ranges. Studies on Fe-Mn crusts and nodules on the continental shelf have not been focused, although their potential is notably diverse, especially in the East Vietnam Sea. Therefore, it is necessary to rely on hydrological - dynamic features in the East Vietnam Sea to determine the distribution of Fe-Mn crusts and nodules and multi-metal nodules.

OCEANOGRAPHIC FEATURES WITH THE POTENTIAL AFFECTING THE FORMATION OF Fe-Mn CRUSTS AND NODULES IN THE EAST VIETNAM SEA

Shallow current in the East Vietnam Sea

Most hydrodynamic studies in the East Vietnam Sea have not mentioned their influence on the formation of the Fe-Mn crusts and nodules. However, long-term current flow studies in the East Vietnam Sea are an important additional scientific basis for the study on the formation of Fe-Mn crusts and nodules.

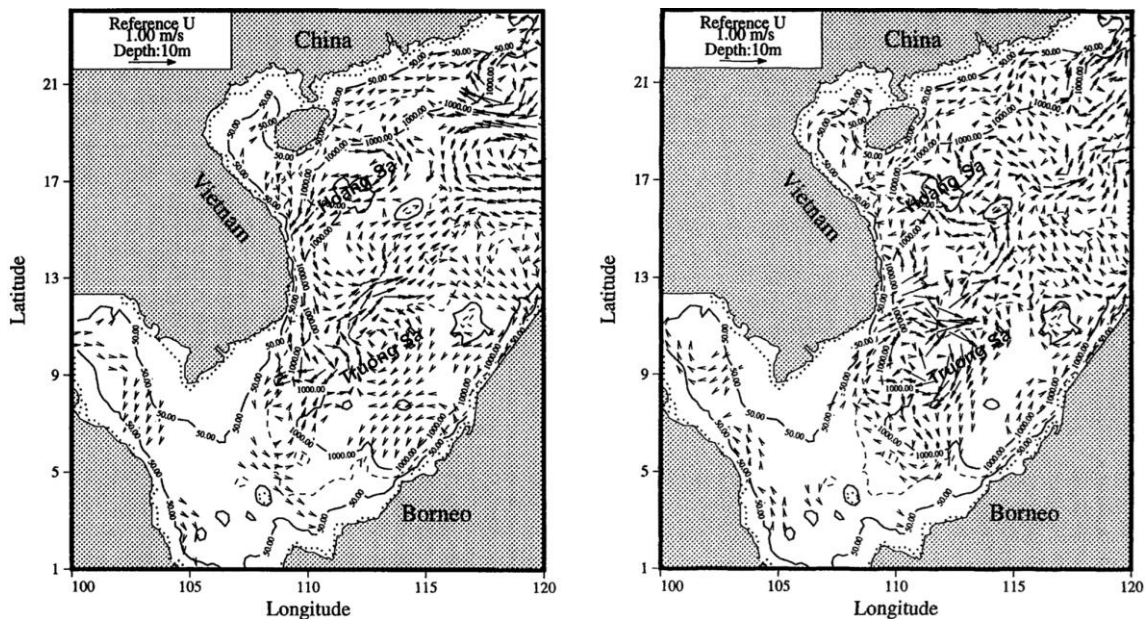


Figure 2. Winter (left) and summer (right) geostrophic currents [15]

Uu & Barankart [15] applied the VIM model to calculate the geostrophic current based on thermohaline data from 1909–1990

(figure 2). The results are more detailed and accurate due to the accuracy of the thermohaline field and confirm the main

features of current by Wyrki [16] and Project 48B.01-01 (1990). Figure 2 indicated the local gyres and their spatial and seasonal fluctuations. Winter saltwater circulation formed the main gyre in the deep sea of the East Vietnam Sea with the strengthening of the current along the central coast of Vietnam. This was explained by the formation of a positive curl wind of wind stress in the deep sea of the East Vietnam Sea when the Northeast monsoon prevails throughout the region. This cyclone is narrowed in the South Central Coast, forming the southeast cyclone with its convergence band in the meridian direction (from meridian 109–110°E). In the western part of Luzon Strait, there is also a relatively stable secondary cyclone in the winter. In the summer, the atmospheric circulation forms two anticyclones

that tend to cover the entire sea area. In addition, a cyclone near the deep Central Coast, this vortex is related to the emerging waters of the South Central Coast due to the wind field differentiation effect near the coast of Vietnam.

Besides in-situ data, the hydrodynamic model is another way to approach the forecasting circulation in the East Vietnam Sea, starting with diagnostic models such as the general current model of Hoang Xuan Nuan [17], Pohlman [18], Shaw & Chao [19], Chao et al., [20]. The most significant circulation results were the general circulation in projects of KC.09.02 and KC.09.24. The results of project KC.09.02 (2005) showed more detail of circulation and indicated the general circulation conditions clearly:

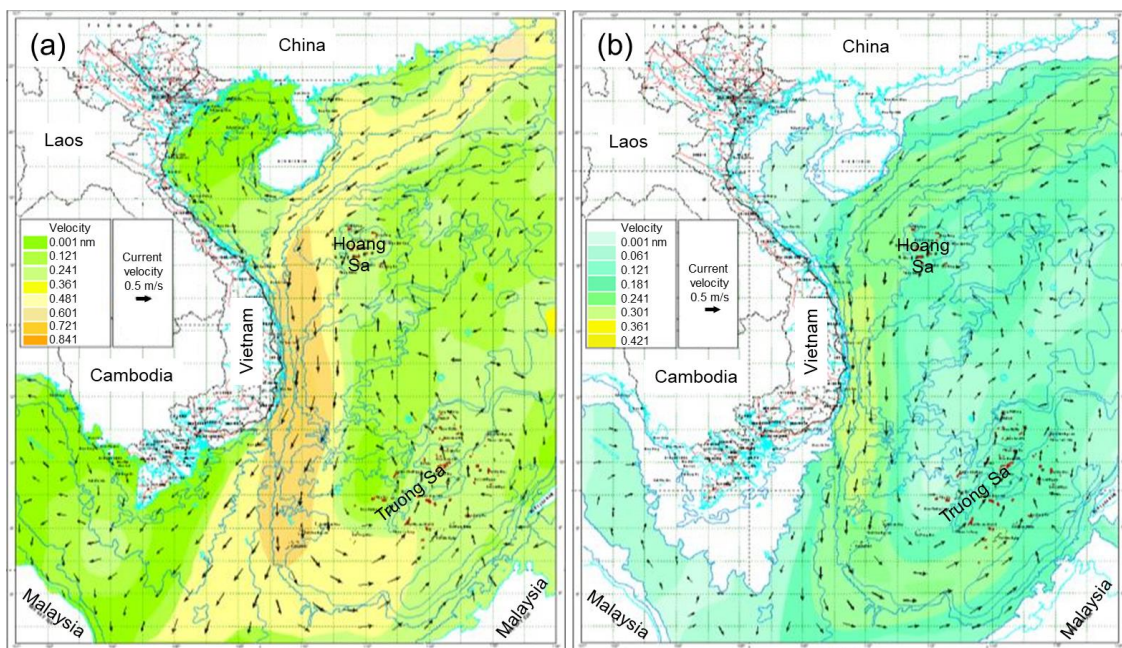


Figure 3. Circulation in the East Vietnam Sea at surface layer (a) and in the 50 m layer (b) in winter (KC.09.02, 2005)

The surface current is strongly influenced by the wind regime. Due to the impact of geostrophic circulation, during the northeast monsoon, the main cyclone gyre is always covering almost all of the East Vietnam Sea (figure 3). In the entire water layer on the seasonal thermal wedge, the circulation features were similar to those of the surface layer. The

circulation system in the 50 m water layer has no significant change compared to surface circulation gyres, but the cyclone gyres develop and dominate the whole East Vietnam Sea. At the water layers beneath the seasonal thermal wedge, the circulation systems are contributed by seafloor topography and weakening wind effect. As a result, the anticyclone gyre at the

center of the East Vietnam Sea is clearer, whereas the two cyclone gyres in the offshore southeastern central and western Luzon Strait are obscure. The cyclone gyre in western Luzon Strait is related to the intrusion of Kuroshio current into the East Vietnam Sea and the enhancement of the current in western East Vietnam Sea. The cyclone gyre in the offshore

southeastern central Luzon Strait and above the seasonal thermal wedge, due to the impact of the local wind field, causes the strengthening of the southward current in the west and the current bending along the isobath lines 100–200 m across the southern continental slope in the East Vietnam Sea (current velocity may exceed 1 m/s).

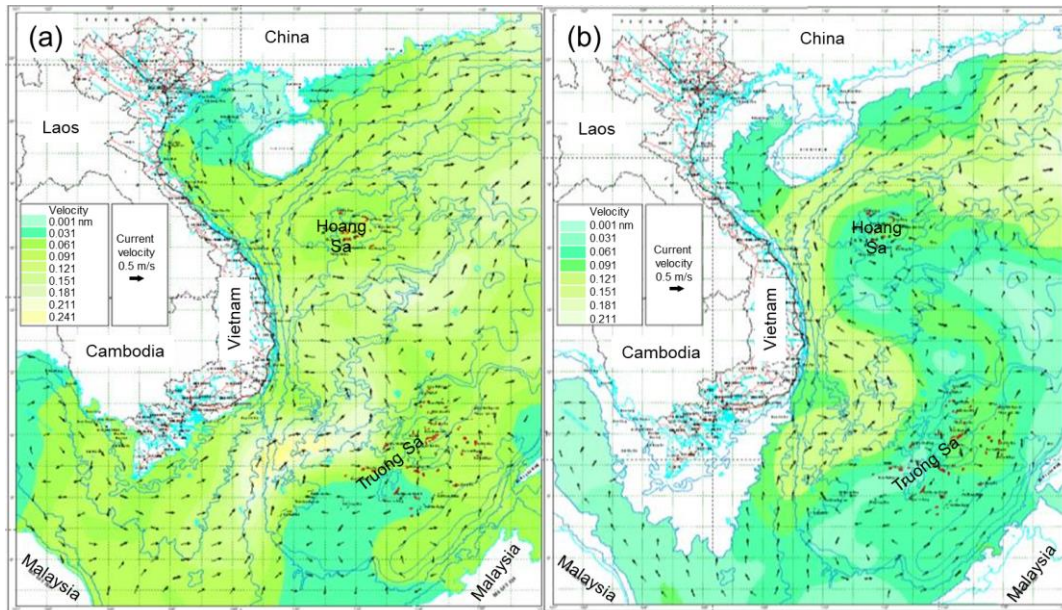


Figure 4. Circulation in the East Vietnam Sea at surface layer (a) and in the 50 m layer (b) in summer (KC.09.02, 2005)

The geostrophic current, which has an anticyclone in the northeastern part of the East Vietnam Sea in both seasons, is formed by effects of the intrusion of Kuroshio current and seawater masses of Pacific Ocean into the East Vietnam Sea.

Due to the relatively shallow and fragmented topography of the Hoang Sa archipelago, a meso-anticyclone gyre is formed in the winter and located between the two cyclone gyres of western Luzon Strait and southeastern Central Vietnam (figure 3).

Under the impact of the Northeast monsoon, there is a tendency to form a branch of southwest current along the Palawan coast towards Borneo. This current, under certain conditions, is the eastern branch of the anticyclone in the center of the East Vietnam Sea.

In the summer, the circulation of the surface layer in the East Vietnam Sea tends to be the opposite of that in the winter due to the dominant role of the wind field on the sea (figures 3, 4). Because the wind speed in summer is smaller than in winter, the surface current velocity in summer is also smaller than in winter, rarely exceeding 50 cm/s. However, the surface current field also has spatial differentiation. Due to the decreasing wind speed in the summer, the circulation in this period was strongly influenced by the thermohaline circulation with the presence of a major anticyclone for the whole East Vietnam Sea. Along with the main northeastward current, local gyres are formed, in which remarkably the anticyclones in the offshore south and north of the East Vietnam Sea are highly stable with position and intensity

reflecting the separation of the main current from the Sunda shelf - Southeast Vietnam.

In the South Central waters, a cyclone gyre is always enhanced due to the differentiation of the wind field with the maximal wind stress (figure 4). In case this cyclone gyre develops, the role of the main anticyclone gyre of origin from a thermal-salt wedge in offshore Central Vietnam (as mentioned above) is weakened, resulting in a southward current along the coast of Vietnam.

In the marine regions from the Gulf of Tonkin to South Central Vietnam, the existence and operation of the summer tropical convergence band lead to the wind field differentiation in the East Vietnam Sea. When the convergence band is located in the north, the southwest and south winds become overwhelming and play a decisive role in the north or northeast general circulation. In the case of the predominant thermohaline convection, this current system along the coasts is oriented towards the south as one branch of the South Centre's cyclone gyre.

Influence of circulation in the onshore South Centre on the activities of upwelling phenomena: when the geostrophic current prevails in the summer (the current direction along the South Central Coast of Vietnam is southward), the upwelling does not take place until there is a divergence circulation of cyclone gyre in the offshore waters (dipole system of circulation). When the Southwest monsoon is stable and strong, the current system along the Central Coast has the direction of north or northeast, the upwelling is appearing. Thus, it is possible to base on the southward current along the coast to determine the boundaries of the upwelling regions.

The cyclone gyre near the Central Coast is developing in the layer water of 0–50 m, whereas the anticyclone gyre in the southeast East Vietnam Sea is mainly in the surface water layer. Generally, in the summer, the circulation of the surface layer in the East Vietnam Sea is still similarly reflected in the 50 m layer.

For the summer circulation of the water layer below the seasonal thermal wedge, the anticyclonic gyre is only present in the southern

East Vietnam Sea, but the cyclonic gyre in the offshore Central Coast is not clear.

The current in the eastern East Vietnam Sea is enhanced by flow into the Pacific at the northern Luzon Strait and the Sulu Sea in the summer. This longshore current is the result of the southwest wind combined with a local cyclone gyre located in the east of the anticyclone in the southern East Vietnam Sea.

Deep current in the East Vietnam Sea

The abysses of the East Vietnam Sea are constantly exchanged by the Pacific Ocean water masses flowing in the deep layer through the Bashi Strait. These deep water masses exist at the depth of 350–1,350 m in the East Vietnam Sea, then again move out of the East Vietnam Sea through the Bashi Strait [21]. It is estimated that the deep water masses in the East Vietnam Sea have a relatively rapid water change time, the residence time is about 40–50 years [22] or even less than 30 years [23]. Although the intermediate water, deep water, and bottom water have the same age and short water exchange time, the source of decomposing matter also creates matter particles small enough to form the nuclei of the colloidal hydrate system in the water bodies.

Xie et al., [24], based on the results of calculating the deep sea circulation and the bottom of the East Vietnam Sea on eight oceanic models with high global resolution (POP, MITgcm, HYCOM, MOM4.0, GFDL gcm, ROMS, LICOM2.0, MOM3), show that temperatures in deeper layers are colder than observed data in World Ocean Atlas, whereas salinity in deep waters on most models is higher than observed data. Water transport through the Luzon Strait below 1,500 m depth is approximately 0.36 Sv ($\text{Sv} \sim 10^6 \text{ m}^3 \cdot \text{s}^{-1}$), less than observed data (about 2.5 Sv). Four homogenous data models and one heterogeneity (OCCAM) show that the current flowing through the bottom threshold in the deep layer at the Luzon Strait reaches the minimum in spring and maximum in winter. The vertically integrated current functions at layers below 2,400 m from these models show the existence of large deep cyclonic gyre in the

East Vietnam Sea, but the differences with the current functions diagnosed from the US Navy's Global Digital Environment Model (GDEM - Version 3.0, GDEMv3) are gained. The inverse structure following the meridian at the water layers below 1,000 m is similar in all models, but the spatial and intensity

distribution in layers below the depth of 1,500 m is completely different between the models. Furthermore, countercurrents following the meridian at the layers below the depth of 2,400 m in these models are weaker than in the GDEMv3, indicating that the process of deep vertical mixing of these models is not large.

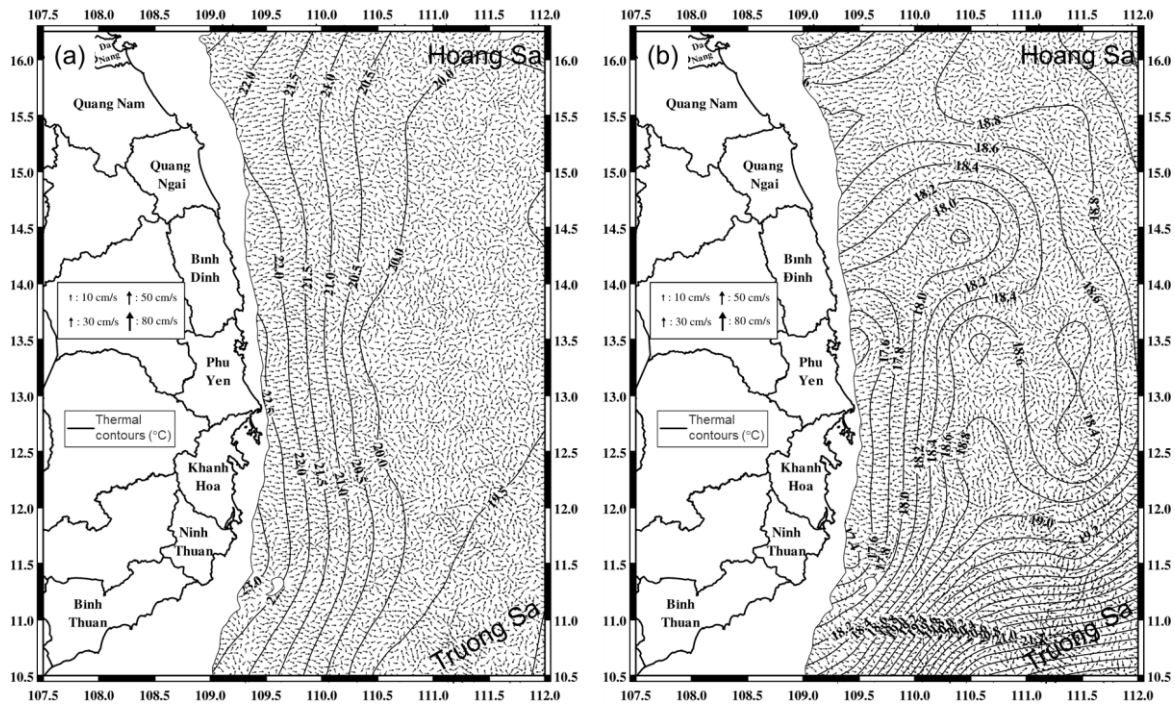


Figure 5. Distribution of the average density current at 100 m layer in January (a) and August (b)

Based on the geostrophic balance method, domestic authors have targeted on deep sea currents. Lanh and Son [25] indicated that at the layer of 150 m in winter, in the western slope of the East Vietnam Sea (the Vietnamese coast), the seasonal average current velocity can reach 20 cm/s, and cyclonic gyres in the north and northwest of the East Vietnam Sea existed at the water layers of 150 m and 500 m with the same scale as in the surface layer, but their intensity decreases rapidly with depth. If at the surface layer, the seasonal average velocity could reach more than 30 cm/s, then it could only reach about less than 5 cm/s at a water layer of 500 m.

The results of 3D model of current from Vietnam - Germany joined project "Investigation and study of upwellings and related processes on the continental shelf of South Central Vietnam" (2003–2007) [26, 27] show the features of the density current in typical months of winter (Northeast monsoon) and summer (Southwest monsoon) at the surface, sub-surface and deep layers (figures 5–7). Based on observed data at three stations of the South Central regions [26, 27], current and tidal current at the deep layer were determined (figures 8, 9). Figure 8 shows that the maximum velocity reached 22 cm/s, the average velocity was 8.5 cm/s; and the current main direction was from east-southeast to the

south-southeast, whereas the tidal current at these depths is not strong and has an axis parallel to the deep isoline (figure 9).

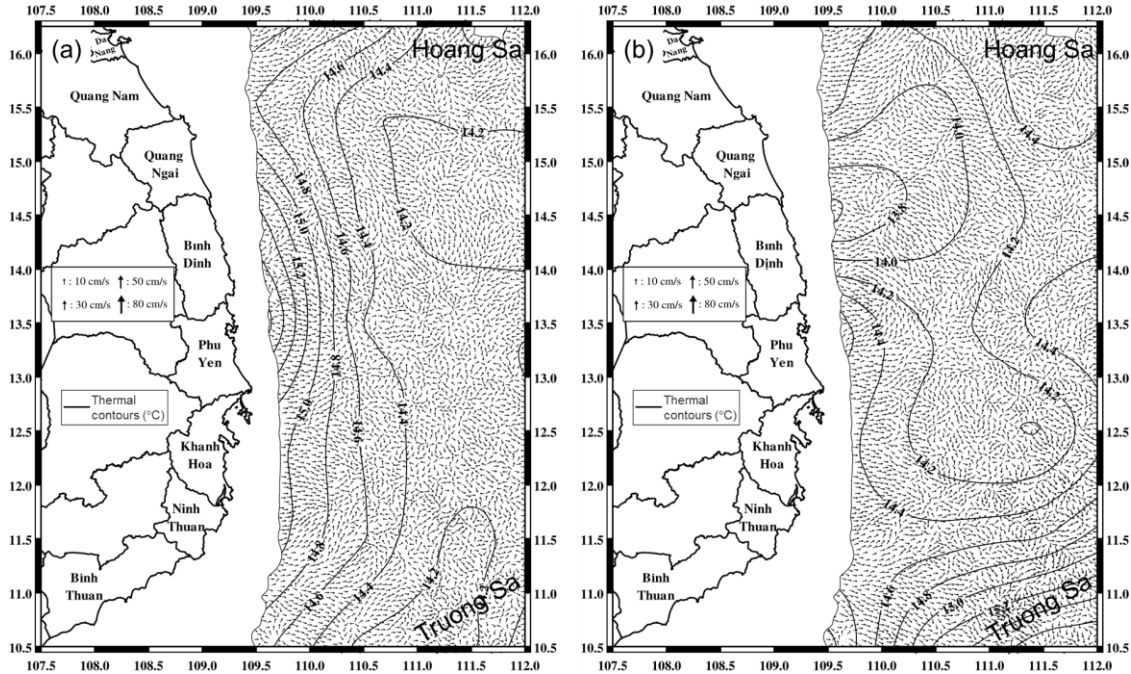


Figure 6. Distribution of the average density current at 200 m layer in January (a) and August (b)

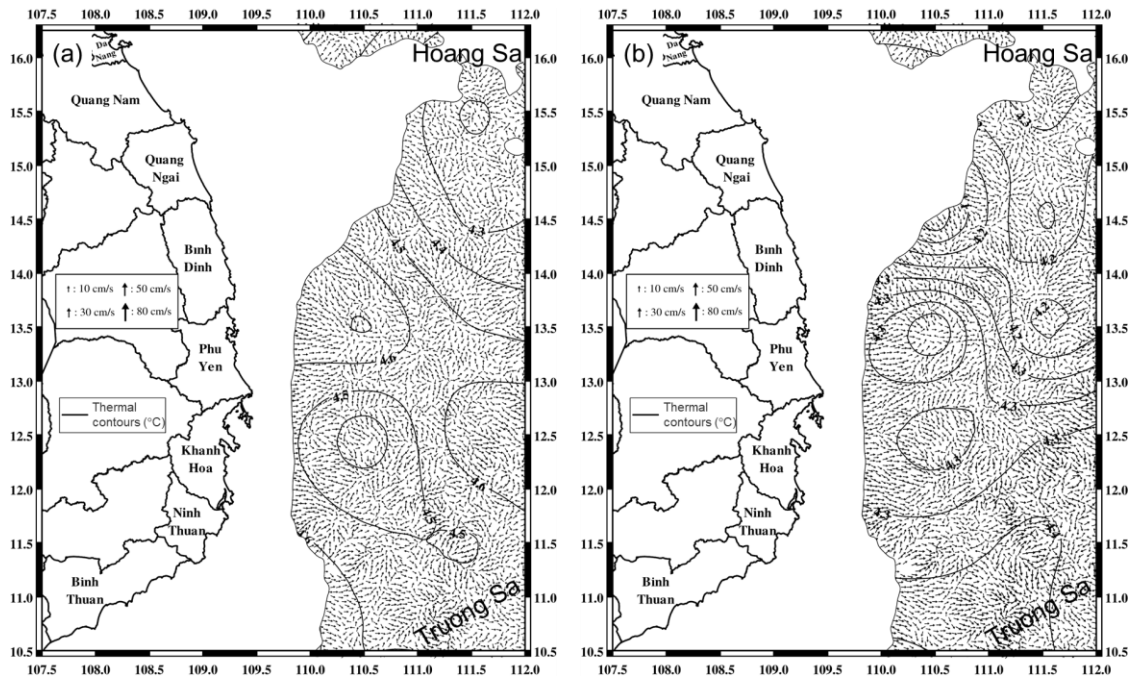


Figure 7. Distribution of the average density current at 1,000 m layer in January (a) and August (b)

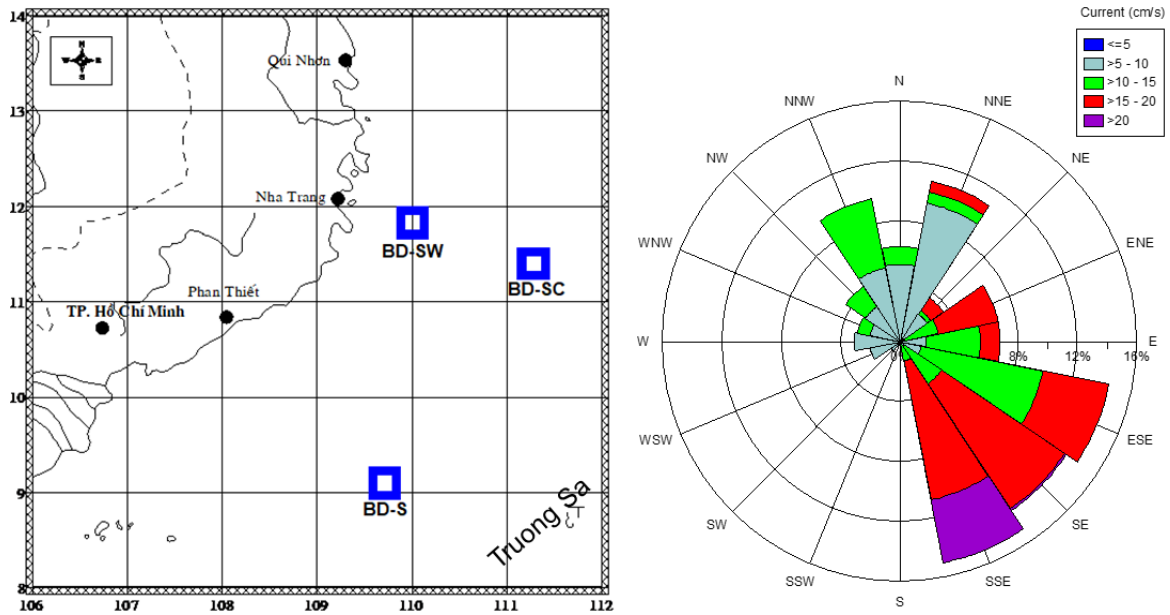


Figure 8. BD-S currents measured at 679 m depth from June 28, 2003 to July 26, 2003

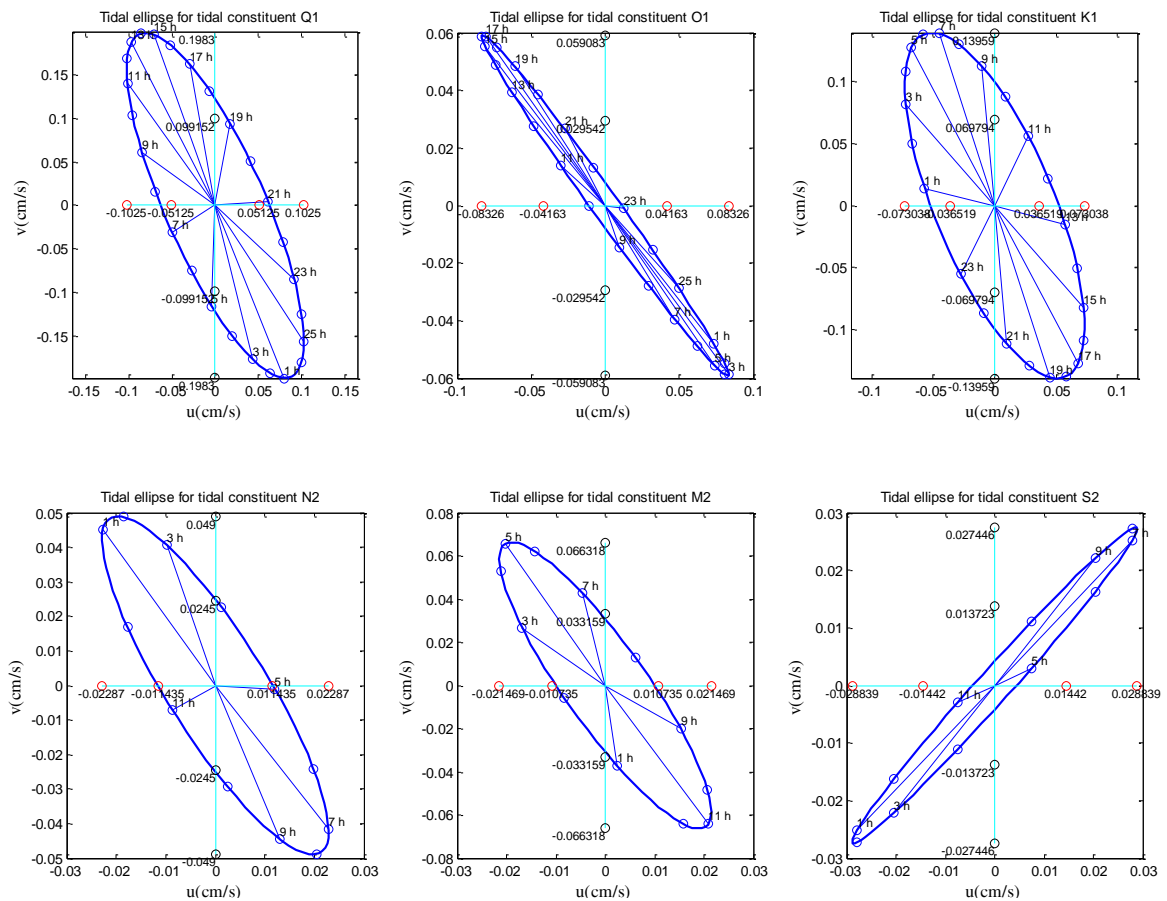


Figure 9. Tidal ellipse of major waves (Q1, O1, K1, N2, M2, S2)

Thus, the circulation in the East Vietnam Sea was a rather complicated structure and fluctuates over time and space:

By depth, water column could be divided into layers: (1) Surface layer (homogeneous) changing seasonally with an average depth of 60–80 m; (2) The layer of sub-surface current (regular current) with a depth of 80–140 m; (3) the sub-deep current layer of 200–1,000 m; and (4) The deep current of 1,000–5,000 m. Each type of flow pattern was associated with features of thermohaline structure with its velocity and direction and having specific causes of formation.

The spatial distribution of circulation in the surface layer consists in macro gyres (regional scale). Inside macro gyres, there are meso-gyres (residence time about 130–140 days and scale of 300–400 km). The spatial distribution and origin of these gyres were not well understood.

Up to now, the understanding of the impact of ENSO on the process of forming flow system fluctuations by depth and space was still at a primitive level.

Luzon Strait (Bashi) plays an important role in the formation of water masses and deep currents in the East Vietnam Sea.

The simulation and calculation of the circulation in the East Vietnam Sea have several advantageous results, but contain some errors, and differ from observed data of various sources (satellite, radar, buoy stations,...).

Upwelling current in the East Vietnam Sea

Upwelling phenomena in Southern waters of Vietnam was first discovered by the Research Program of East Vietnam Sea and Gulf of Thailand (NAGA) of the US between 1959 and 1960. In this program, the upwelling was discovered through the analysis of the hydrodynamic distribution and structure, such as seawater temperature, salinity, and density. It is found that the marine regions of coastal waters and shelves in the South Central Vietnam had low temperature, high salinity, and high density, as a result of upwelling water from the bottom [16].

After the year of 1975, the upwelling in the coastal waters of Southern Vietnam continued to be studied by a series of projects

on the physical and hydrological conditions of the marine regions from Thuan Hai to Minh Hai (1978–1980); on the hydrological physics of the Southern Vietnam continental shelf - code 48.06.01 (1981–1985), on the hydrological and dynamic structure of the East Vietnam Sea - code 48B.01.01 (1986–1990) and especially, in the project on the strong upwellings in the South Central waters - code KT03.05 (1991–1995).

Up to now, only five major projects that carried out the cruises have been done in the marine region of Southern Vietnam, including the NAGA Program (1959–1960), the Thuan Hai - Minh Hai program (1978–1980), the project KT03-05 (1991–1995), Vietnam - Germany joint project (2003–2007, 2009–2010), and Vietnam - United States joint project (2013–2015), among which only the 3rd and 4th projects were targeted towards the strong upwellings in the South Central waters. In these projects, the factors of physics (meteorology, hydrology and flow), hydrology, geochemistry, aquatic and some special ecological effects are observed simultaneously to orient the study of geometrical and physical features of upwelling, as well as upwelling ecological consequences, the influences of the Mekong's water masses on upwelling area.

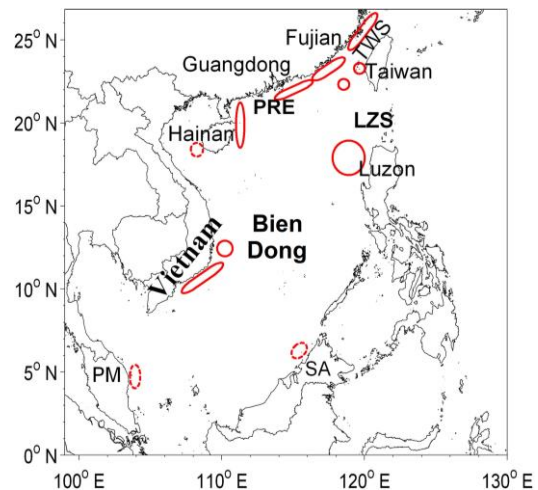


Figure 10. Upwelling areas in the East Vietnam Sea [30]

Generally, nine main upwelling areas (appearing regularly) and three weak upwelling

areas (appearing irregularly) have been identified in the East Vietnam Sea [28–30] (figure 10), in which the main upwelling area is located in the waters of the Ninh Thuan - Binh Thuan and offshore regions of Khanh Hoa.

The calculation results in the South Central upwelling regions under the Vietnam-Germany joint project indicated:

Upwelling exists in the waters along the coast and South Central shelf, from Binh Dinh to Binh Thuan. The strongest upwelling center was observed in the waters and shelf of Ninh Thuan - Northern Binh Thuan. Upwelling current comes from layers deeper than 200 m.

Upwelling is strongly active in the seasonal cycle and synoptic period. It normally occurs from May to September, in which the strongest was in June, July and August. The synoptic period could be active in the period from 2–3 days to 8–9 days, this period is the same as the synoptic period of the Southwest monsoon.

Upwelling intensity: in the strongest upwelling center (waters of Ninh Thuan - Binh Thuan), the upwelling current velocity in synoptic oscillation can reach 10^{-2} – 10^{-1} cm/s, whereas in the seasonal cycle it can reach 10^{-4} – 10^{-3} cm/s. Maximum upwelling velocity was found in the water layers when water masses moved from the 200 m depth, getting smaller as it went up and reached 0 at the sea surface: At the depth of 10 m, the vertical flow distribution can reach 0.11 cm/s upward, and -0.027 cm/s downward; at a depth of 50 m, when the influence of the wind was completely reduced, the upwelling can reach 0.054 cm/s upward, and -0.050 cm/s downward; at the depth of 100 m, the maximum upward vertical velocity is 0.043 cm/s, the maximum downward vertical velocity is -0.024 cm/s; and at the 150 m layer, the upward vertical velocity had a maximum value of 0.016 cm/s and the maximum downward value was -0.017 cm/s.

The cause, and variation in intensity and the scale of the upwelling area in the South Central regions have local features. The upwelling is the result of the interactions among physical processes (interaction between atmosphere - ocean, topographic bottom - shoreline in the region), Ekman transport,

interactions between strong downward current systems in the western East Vietnam Sea and the strong upward current system from the Sunda shelf; and affected by the Coriolis changes in the coastal waters.

BIOLOGICAL FEATURES AFFECTING Fe - Mn CRUST AND NODULE FORMATION PROCESS IN THE EAST VIETNAM SEA

Microorganisms play an important role in the iron-manganese nodule forming process in seawater. They involve the biological processes (bio-mineralization) of the formation of multi-metal nodules. Round- and rod-shaped bacteria, equally abundant in the seawater of the nodules, could form a biofilm around nodules that promoted the precipitating process of metal oxides on nodules' surface, in reactions including the oxidation of dissolved Mn (II) into insoluble Mn (III, IV). The study on microbial diversity in multi-metal and Fe-Mn nodules has been done by modern and traditional methods, but knowledge of the diversity of microorganisms associated with the Fe-Mn nodules is very limited in the oceans. In the East Vietnam Sea, Zhang et al., [31] indicated a genetic library of bacterial diversity around Fe-Mn nodules with 11 isolated strains of bacteria. The majority of these strains belonged to Proteobacteria; a few in Firmicutes. A total of 259 strains of 16S rRNA gene sequences of bacteria were identified, in which Gammaproteobacteria was predominant, with *Pseudomonas* and *Alteromonas* as the most abundant strains. Among them, many strains of bacteria could be capable of oxidizing manganese, reducing iron, oxidizing hydrogen, and methylotrophs.

Research on the role of microorganisms in the process of Fe-Mn crust and nodule formation, Ehrlich [32] showed that microorganisms play an important role in forming the beginning nucleus of the nodules. When the Fe-Mn and multi-metal nodules are broken down into small pieces, two micro-bacteria types (round- and rod-shaped) are detected. According to Ehrlich [32], in the process of forming Fe-Mn nodules, Mn oxidation firstly involves the participation of

microorganisms in two ways: direct oxidation of Mn (II) or indirect reaction through the absorption of protons incorporated in the ATP reaction of respiration. Meanwhile, bacteria and archaea involved in the formation of nodules surrounded by S-shaped structures absorbed Mn (II) ions on their surface [33], thereby forming a layer covering 10 m to 25 nm and consisting of microscopic units interspersed with proteins or glycoproteins with Mn (II) and Mn (IV) ions. Thanks to this ability, bacteria create larger and more complex structures with high surface charge, an organic coating that protects microorganisms and increases absorption/adhesion/mineralization with metal ions. During the biological mineralization process occurring on the surface of bacteria, the Mn and Fe oxygen-hydroxide ions or colloids are absorbed and mineralized, forming Mn (IV) or Fe (III) agglutination. After that, the physicochemical process continues to create the Fe-Mn crust and nodule in the East Vietnam Sea.

CONCLUSION AND DISCUSSION

Due to the complexity of the studied issues and the limitations of the sources of data and documents, in the framework of this paper, we have some conclusions and discussions as follows:

- The East Vietnam Sea has many favorable conditions for the formation of Fe-Mn crust and nodules: complex terrain - several seamounts, current flow, and the geostrophic current system, water exchanges between the East Vietnam Sea and the Pacific Ocean, and the Indian Ocean changing seasonally, and strong upwelling phenomena.

- Regarding material resources and material sedimentation capacity in the East Vietnam Sea, it is necessary to pay attention to and clarify several issues: (1) Variation in the scale of regular or seasonal circulation systems and gyres with dynamic systems (spatial and temporal changes); (2) For gyres in areas in the East Vietnam Sea, if they are in microscale (less than 100 km in space), it is needed to detail the dynamic process of transport substance by layer and horizontal direction, whereas if they are in mesoscale (over 100 km

in terms of space), it is needed to clarify the vertical transport process (masses). Cyclone gyres involve the transport from the lower layers to the upper layers whereas the anticyclone is the opposite one.

Especially the oxygen-minimum layer is located in the range of 300–1,200 m, which can enhance the ability to form Fe-Mn crust and nodules. Combination of hydrodynamic conditions (current regime, upwelling current, and downwelling current), topography (continental shelf, the slope of seamounts), material resources, oxygen-minimum layer, and microorganism distribution has created physical-biochemical conditions suitable for the process of Fe-Mn crust and nodule formation. The Fe-Mn crust and nodule formation begins with the accumulation of Mn and Fe oxygen-hydroxide ions or colloids on the surface of the nucleus surrounded by mineralizing bacteria. These processes take millions of years for the crust and nodule formation, therefore, besides identifying the potential Fe-Mn nodule forming area to exploit marine economic development, the rational use of mineral resources is also an effective solution to achieve sustainable marine economic development.

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