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STUDY OF GAS GEOCHEMISTRY IN THE SEDIMENTS OF THE SOUTHWEST SUB-BASIN, EAST VIETNAM SEA

SUMMARY OF DISSERTATION IN EARTH SCIENCES

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PREFACE

1. The urgency of the thesis

The East Vietnam Sea has garnered significant attention from scientists worldwide in recent decades. However, there has yet to no research on the gas distribution in the sediments in the southern part of the sea, with the southwestern sub-basin East Vietnam Sea as a typical example. Additionally, most marine mineral geological investigation studies in Vietnam focus on areas from 100 meters of water depth and upwards. However, there have been very few detailed studies in the deep sea. Moreover, the gas geochemical characteristics in the surface sediments are vital indicators and prerequisites for assessing the potential of oil and gas fields in the study area.

Therefore, the thesis title **"**Study of gas geochemistry in the sediments of the southwest sub-basin, East Vietnam Sea", is proposed, which will contribute to solving the urgent problems mentioned above.

2. Objective and content of the thesis

❖ ***Objective:***

Elucidate the geochemical characteristics of hydrocarbons, hydrogen, helium, and carbon dioxide in the surface sediments of the southwest sub-basin of the East Vietnam Sea. This information will be the basis for assessing and delineating promising oil and gas areas within the study region.

❖ ***Contents:***

- Study the composition and origin of hydrocarbons, hydrogen, helium, and carbon dioxide in the surface sediments of the southwest sub-basin of the East Vietnam Sea.

- Study the distribution characteristics of hydrocarbons, hydrogen, helium, and carbon dioxide in the surface sediments of the

southwest sub-basin of the East Vietnam Sea, thereby indicating potential oil and gas areas in the study area.

3. Defensive thesis

❖ ***Defensive thesis 1:***

Methane gas in the surface sediments of the study area has a high content, which is superior to other hydrocarbon gases. The concentration of gases in the surface sediments collected in the Nam Con Son basin (BTNCS) is much higher than in the southwest sub-basin of the East Vietnam Sea (KVPTS). Hydrocarbon gas in the surface sediments of the study area originates from two sources: deep heat in the eastern area of the Nam Con Son basin and a mixed origin in the southwest sub-basin of the East Vietnam Sea. The East Vietnam slope fault system (109° meridian) and the northeast-southwest fault system, can act as the main conduit for gases of deep thermal origin in this area.

❖ ***Defensive thesis 2:***

In the study area, the concentration of hydrocarbons decreases from West to East with increasing water column depth. There exists a broad hydrocarbon outgassing zone, distributed in a wide range from 8°25' to nearly 9°40' North latitude, along the continental slope of the Nam Con Son basin. The background content of methane in surface sediments decreases from south to north when comparing the southwestern deep-lying East Sea with the Phu Khanh basin and Song Hong basin, with values of 103 ppm, 34 ppm, and 26 ppm, respectively.

4. Material

During the implementation of the thesis, the Ph.D. student collected 39 gas samples from surface sediments. These samples were obtained from 19 gravity cores in the study area during two expeditions. The first expedition was conducted aboard the DK105

ship in August and September 2019, while the second expedition took place on the R/V Akademik Lavrentyev in November 2019.

These expeditions respectively belong to Vietnam's National Research Program KC09/16-20 and the international cooperation project "The 1st survey, geological, geophysical, and oceanographic research between VAST and FEBRAS by ship Academician Lavrentyev in Vietnamese waters" with the code QTRU.02.05/19-20. To serve the research content of the thesis, the Ph.D. student also collected and synthesized the results of the analysis of surface sediment samples under the project “Study on characteristics of seabed mud and clay in the southwest sub-basin of the East Vietnam Sea and their applicability” with the code VAST05.03/20-21, conducted by Ph.D. student and other researchers.

In addition, the PhD student has collected various documents, including published works, reports on scientific topics, and maps relevant to the research field and the study area.

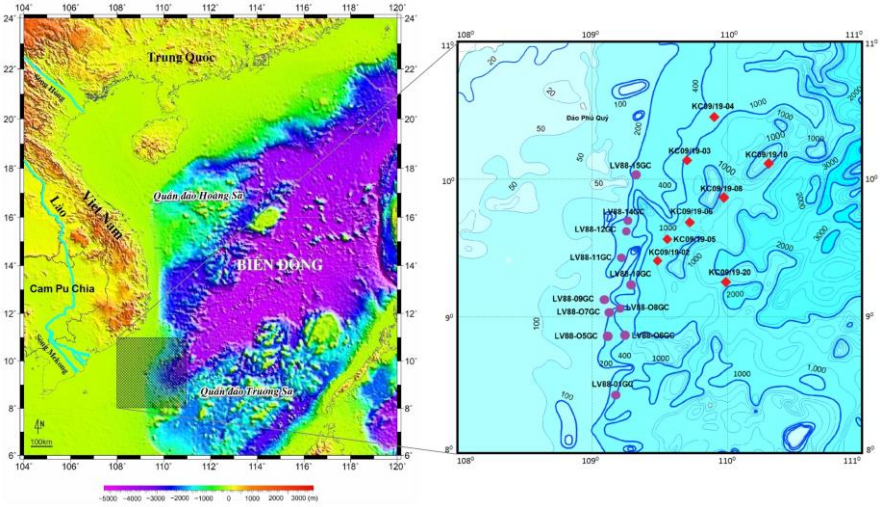

Figure 1. Location of gravity cores in the southwest sub-basin of the East Vietnam Sea from two expeditions of DK105 (red diamond) and Lavrentyev (violet circle)

5. New contribution of the thesis

The hydrocarbons, helium, hydrogen, and carbonic gases in the surface sediments of the southwest sub-basin of the East Vietnam Sea, particularly Vietnam in general, have been studied in detail. The thesis has obtained a set of gas geochemical datasets in the surface sediments in the study area. These are geochemical data in surface sediments in the southwest sub-basin of the East Vietnam Sea, published for the first time in specialized journals at home and abroad.

The thesis has studied the gas geochemical characteristics in surface sediments in the southwest sub-basin of the East Vietnam Sea. It has determined hydrocarbons, carbonic, helium, and hydrogen composition and distribution characteristics. The thesis has identified the origin of gaseous components in sediments in the study area based on research results using modern methods such as hydrocarbon gas ratios, carbon isotopes, sediment geochemistry, and statistical analysis.

The thesis has proposed a large-scale gas emission zone in the study area from the interpretation of gas geochemical data combined with previous research documents.

CHAPTER 1. NATURAL CHARACTERISTICS OF THE STUDY AREA

1.1. Geographical location and topographical features of the study area

The study area is in the southwestern of the East Vietnam Sea. The study area is within limits: From 9°N to 11°N, 109°E to 111°E, extending from the south-central continental shelf to the southwestern sub-basin of the East Vietnam Sea (Figure 1). The topography of the area is generally quite complicated. The section in this area clearly shows the continuity of a typical continental margin,

including continental shelf, continental slope, deep seabed, and submarine island.

1.2. Meteorological and hydrographic characteristics of the study area

The study area is in a typical tropical monsoon climate, with slight seasonal variation, almost hot all year round. The study area is a small part of the East Vietnam Sea, so the hydrographic characteristics depend on the oceanographic activities of the East Vietnam Sea.

1.3. Geological settings

1.3.1. Overview

The East Vietnam Sea is situated at the junction of the Eurasian, Pacific, and Indo-Australian plates. The opening of the East Vietnam Sea reveals complex patterns of continental breakup and seafloor spreading in the Cenozoic. In recent decades, many geological and geophysical studies have been conducted in the southwestern of the East Vietnam Sea

1.3.2. Stratigraphy

Stratigraphic characteristics in the study area are summarized in two basins Tu Chinh - Vung May and Nam Con Son. Cenozoic formations include:

Paleogene:

- Oligocene sediments: Including Vung May formation (E_2-E_3?vm) and Cau formation (E_3c)

Neogen:

- Lower Miocene sediments include Phuc Nguyen Formation (N_1^1pn) and Dua Formation (N_1^1d):

- Middle Miocene sediments include Tu Chinh formation (N_1^2tc) and Thong - Mang Cau formation (N_1^2t-mc):

- Upper Miocene (N13) sediments include Phuc Tan Formation (N_1^3ph) and Nam Con Son Formation (N_1^3ncs).

Pliocene - Quaternary sediments

In the Nam Con Son basin, the Pliocene - Quaternary formations were grafted into the East Vietnam Sea formation, with foundation thickness near the Con Son ledge and gradually increasing to the east to 2000 m. The East Vietnam Sea formation is related to the Pliocene transgression.

Promising oil and gas formations in Nam Con Son basin discovered so far are mainly Oligocene sediments (Cau Formation) rich in marshy organic matter, distributed in trenches, and Early Miocene sediments (Dua Formation) widely distributed in the basin.

1.3.3. Magmatic activities

The studied area has complex magma activity. Cenozoic magmatic activity throughout the East Vietnam Sea, in general, and in the study area, has very strong Pliocene - Quaternary basalt volcanic activity.

1.3.4. Cenozoic tectonic activities

The main fault systems in the region develop in the Northeast - Southwest and Northwest - Southeast directions. The 109^0 meridian fault lies entirely in the study area and dramatically influences the tectonic structure of this area.

CHAPTER 2. THEORETICAL BASIS AND METHODS

2.1. Theoretical basis

2.1.1. Theoretical basis of gasgeochemistry in sediment

2.1.1.1. General concept

The gasgeochemical method for mineral prospecting has been applied for a long time. Gasgeochemistry is a branch of geochemistry that studies the distribution, origin, movement, and potential use of natural gas as an industrial feedstock.

The research content of the thesis is to study the characteristics and decipher the origin and distribution rules of gas geochemical components in surface sediments in the southwest sub-

basin of the East Vietnam Sea. The studied gas composition is mainly hydrocarbon, helium, and hydrogen gas.

2.1.1.2. Theoretical basis of hydrocarbon gas origin

a. Oil and gas origin

Previous studies have shown that the gas composition in the bottom sediments and seawater is closely related to the biological origin or the deep thermal origin. Advances in science today have helped solidify the view of the organic origin of oil and gas.

b. The process of converting and forming hydrocarbon gas

Previous studies have shown that hydrocarbons in sediments and seawater are formed from two main sources: 1) due to the decomposition of organisms; 2) is the product of deep hydrocarbon metabolism.

c. Studying the origin of hydrocarbon gas in sediments in seas and oceans worldwide based on hydrocarbon gas ratios and isotopic composition

Regarding identifying hydrocarbon gas origin, the ratios C1/(C2+C3), C1/C2, C2/C2:1, (C2+C3)/C1 are important ratios that have been used for a long time. The symbols C1, C2, C2:1, and C3 represent the contents of methane, ethane, ethylene, and propane, respectively. In addition, the value of the carbon isotope composition of methane in sediments in many different seas around the world has also been reported.

d. Distribution of hydrocarbons in sediments in seas and oceans around the world

The distribution of hydrocarbons in sediments in the seas and oceans of the world has been studied by scientists quite early in most of the oceans and large seas. The results show that the concentration of hydrocarbon gases in the sediment is much higher than in seawater. Since then, the authors have shown that gases of deep origin and gases of biological origin from the decomposition

activities of organic compounds by microorganisms are the primary sources of hydrocarbon gas in sediments.

e. The distribution and origin of the helium and hydrogen gases

Studies have shown that the distribution and origin of helium and hydrogen gases are related to intraplate and fringe magma activity, deep faults, and hydrothermal systems.

2.1.2. The situation of geological and mineral research in the seabed and oceans in the world and the East Vietnam Sea

The world's leading countries in research, exploration, and exploitation of minerals in the sea and ocean include Japan, the US, Russia, Australia, China... In Vietnam, national scientific and technological projects on marine research have been implemented, and there have been some achievements in geology, geophysics, and the environment of the East Vietnam Sea. However, those topics and projects are still only basic studies on geology, tectonics, geodynamics, environment, and promising mineral zoning in the East Vietnam Sea without direct studies on gas-geochemical characteristics in the East Vietnam Sea sediments, of which the southwest sub-basin of the East Vietnam Sea is a typical example.

2.1.3. Situation of gas geochemical research in the East Vietnam Sea and the study area

Between 1980 and 1995, gas geochemical studies for the search for solid minerals and petroleum in our country were conducted using research ships of the Soviet Union (later the Russian Federation). In a recent study, the authors proposed that the East Vietnam Sea is located in the gas hydrate belt of Pacific East Asia (Eastern Asia gas hydrate belt). However, there needs to be a study on the gas distribution in the sediments in the southern part of the East Vietnaam Sea, including the southwest sub-basin of the East Vietnam Sea.

In the East Vietnam Sea, in recent years, there have been survey trips by marine research cruise Akademik Boris Petrov in 2017 and research cruise Akademik M.A Lavrentyev in November 2019 in the western waters of the East Vietnam Sea. Many important geophysical, geological and oceanographic data have been obtained during these expeditions and have provided important new geochemical and mineralogical features of the Vietnamese continental shelf and adjacent basins.

2.2. Method

The methods applied in the thesis include method of data synthesis and processing, field survey and sampling at the sea, method of analysis of grain composition, method of analysis of main element composition, method of analysis of trace element, method of organic geochemical analysis, method of extraction and analysis of gas from surface sediment samples, method of calculating background, anomaly, and threshold.

CHAPTER 3. GASGEOCHEMICAL CHARACTERISTIC OF SURFACE SEDIMENT IN THE SOUTHWEST SUB-BASIN OF THE EAST VIETNAM SEA

3.1. Gas composition in the surface sediments in the southwest sub-basin of the East Vietnam Sea

3.1.1. Gas composition

Gases determined in the surface sediments in the southwest sub-basin of the East Vietnam Sea include carbon dioxide, helium, hydrogen, methane, ethylene, ethane, propane, butane, and i-butane.

For the entire study area, the methane content in surface sediments ranges from 0.5 ppm to 440 ppm. Methane gas detected in surface sediment samples in the Nam Con Son basin (BTNCS) is many times higher than in samples from the southwest sub-basin area of the East Vietnam Sea (KVPTS). Ethylene, ethane, and propane gases have concentrations ranging from 0 - 70 ppm, 0 - 124 ppm, and 0 - 50 ppm, respectively. Butane gas is presented with two isoforms,

butane and i-butane; in surface sediment samples of the KVPTS, only some of these two gases were detected. At BTNCS, butane and i-butane gas concentrations in surface sediments ranged from 0 to 8 ppm and 0 to 5.27 ppm, respectively.

Carbon dioxide in surface sediments ranges from 0.07% to 3.13% throughout the study area. Hydrogen content in the study area sediments ranges from 0.2 ppm to 148.3 ppm. Meanwhile, the content of helium gas ranges from 0 to 12.7 ppm. The content of carbon dioxide, hydrogen, and helium gases in the surface sediments in the BTNCS is higher than in the KVPTS. However, some sites in the KVPTS have significantly higher concentrations of hydrogen and helium in surface sediments than some sites in the BTNCS.

3.1.2. Calculation results of background content, threshold and anomalous values of gases in surface sediments in the southwest sub-basin area of the East Vietnam Sea

The calculation of background content, threshold, and anomalous values of gases in surface sediments in the southwest sub-basin area of the East Vietnam Sea will be carried out with the two areas of the BTNCS and the KVPTS to ensure the similarity in geological structure in these two areas. The boxplot method determined the geochemical data sets' threshold and anomalous values. The outstanding point that can be seen is the outlier value of the methane content in the surface sediments in the BTNCS compared to the KVPTS. While no anomalous values were detected at KVPTS, 02 positive outliers were detected. The background content of methane gas is 2.2 ppm and 103 ppm for the KVPTS and the BTNCS, respectively.

Similar to the above, at the KVPTS, one positive anomaly of ethylene gas was detected in the surface sediments, and at the BTNCS, 04 positive anomalies were detected. The corresponding background content of ethylene gas for KVPTS and BTNCS is 0.11

ppm and 7.45 ppm. There is one positive anomaly for ethane gas at KVPTS and BTNCS, respectively. The background content of ethane of KVPTS and BTNCS was determined to be 0.0056 ppm and 24.2 ppm.

For propane gas in surface sediments, one positive anomaly was detected in the NR, and three positive anomalies were detected in the NR. The background content of propane gas calculated for the KVPTS and NRCS is 0.029 ppm and 5.92 ppm, respectively.

There are 04 positive anomalies detected for butane gas in surface sediments at BTNCS. The background content of the butane gas of BTNCS was determined to be 0.625 ppm.

Through statistical analysis, no anomalies of carbon dioxide were detected in surface sediments in both sequences. The background content of carbon dioxide of the KVPTS and the NR is 0.14% and 3.13%, respectively.

One point and two positive anomalies were detected at KVPTS and BTNCS for helium gas, respectively. The background content of helium gas was determined to be 1.12 ppm and 1.99 ppm.

At BTNCS, 02 positive anomalies of hydrogen gas were detected. The background content of hydrogen gas in this area is calculated to be 7.83 ppm and 9.04 ppm for the KVPTS and the BTNCS, respectively.

3.2. Origin of gases in the surface sediment in the southwest sub-basin of the East Vietnam Sea

3.2.1. Interpretation of hydrocarbon gas origin according to hydrocarbon ratios

3.2.1.1. Interpretation the origin of hydrocarbon gas according to the ratio C1/(C2+C3)

According to previous studies, when the values of the ratio C1/(C2+C3) are more significant than 1000, it is a sign of hydrocarbon gas of biological origin, which is the product of the

decomposition of organic matter by microorganisms. While a value less than 50 will indicate a thermal origin, and values between 50-1000 are a mixed source index. The ratio of C1/(C2+C3) of hydrocarbon gas in the surface sediments in the BTNCS is almost significantly lower than in the NR, with values mostly less than 10 (Figure 3.1), indicating that hydrocarbon gas in surface sediment samples in the NR has a thermal origin, while in NR, hydrocarbon gas has mixed origin (biological source + thermal origin).

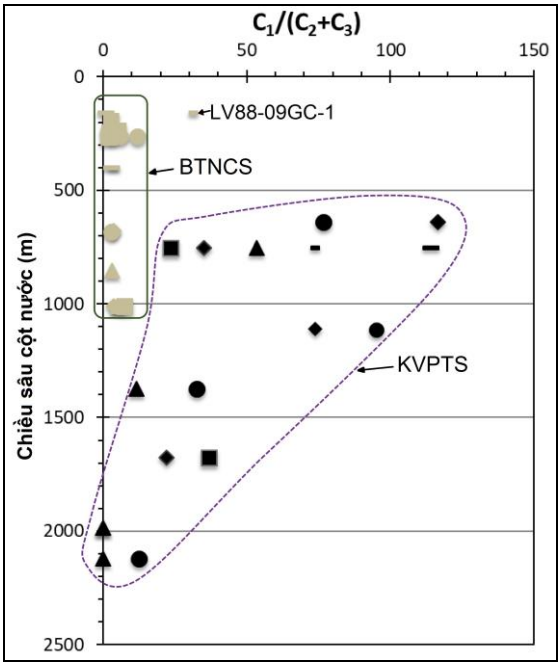

Figure 3.1. Ratio of C1/(C2+C3) of methane, ethane, and propane in surface sediments according to water column depth

3.2.1.2. Interpretation the origin of hydrocarbon gas according to the ratio C_1/C_2

The ratio of C1/C2 of methane and ethane in surface sediments in the BTNCS is significantly lower than that of the KVPTS. The value suggests that the hydrocarbon gas in the BTNCS

has a deep thermal origin, while the hydrocarbon gas in the NR is of mixed origin.

3.2.1.3. Interpretation of the origin of hydrocarbon gas according to the ratio (C_2+C_3)/C_1

According to previous studies, when the ratio (C2+C3)/C1 is less than 0.1 is an indicator of gases originating from existing sediments. In contrast, when this ratio is greater than 0.1, it indicates gases of oil and gas origin. The ratio (C2+C3)/C1 at the KVPTS is all less than 0.1; at the BTNCS, most values are higher than 0.1. Therefore, the hydrocarbon gas in the surface sediment samples at the KVPTS is derived from modern sediments, the decomposition product of organic matter in modern sediments by microorganisms. Meanwhile, hydrocarbon gas in surface sediment samples at the BTNCS is of oil and gas origin, brought up from deep below.

3.2.1.4. Interpretation of the origin of hydrocarbon gas according to the ratio $C_2/C_{2:1}$

The ratio of C2/C2:1 of ethane and ethylene gases in the surface sediments in the KVPTS is much smaller than in the BTNCS, with all values being less than 0.5 or 0. The range reinforces the statement about the mixed origin. However, it favors the biological source of hydrocarbons in the surface sediment samples in the KVPTS and the thermal origin of the hydrocarbons in the BTNCS.

3.2.2. Interpretation of the origin of hydrocarbons according to carbon isotopes

The isotope composition δ13C of methane in surface sediments in the study area mostly gives the value of heavy isotope from -29.4‰ to -25.7‰. Comparison with previous studies shows that the methane in the study area is mainly of thermal origin. The values of isotope composition δ13C of carbon dioxide in surface sediments ranged from -24.8‰ to -17.6‰, which is an indication of the gas originating from the thermal decomposition of organic matter, usually a product of coal or petroleum production (Figure 3.2).

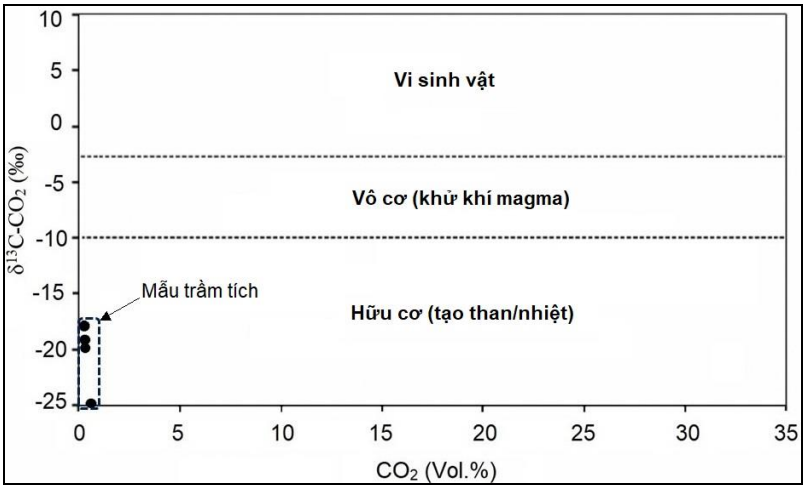

Figure 3.2. Situation of 13C isotope composition of carbon dioxide in surface sediments in the study area

3.2.3. The relationship between surface sediment and gas characteristics in surface sediments in the southwest sub-basin of the East Vietnam Sea

3.2.3.1. The relationship between the geochemical characteristics of the surface sediments and the gas characteristics in the surface sediments in the southwest sub-basin of the East Vietnam Sea

The analytical results show that the surface sediment samples in the study area are all clay or silty clay with predominant clay content with negligible content of sand. The content of oxides such as SiO_2, Al_2O_3, CaO, and Fe_2O_3 is higher than other oxides. The trace elements determined content include Ag, As, Ba, Bi, Cd, Cs, Co, Cr, Cu, Mo, Ni, Pb, Sb, Sr, Zn, Sc, Y, and 15 lanthanide series elements. The chondrite normalization graph of rare earth elements shows that the surface sediment samples in the study area have all continental sources. Total organic carbon content in the samples ranged from 0.18 to 1.45%, with an average of 0.83%. Protein content in the samples ranged from 0.26 to 0.52%. The total sulfur values in the samples LV88-12GC-1 and LV88-12GC-2 were significantly higher than the others. Besides, the total nitrogen content in the samples ranged from 0.067 to 0.106 %.

Based on statistical analysis for each trace element, positive anomalous values of elements Mo, As, Cu, and Pb were detected. These anomalies are mainly concentrated in the LV88-12GC core with very high values compared to other samples. Cores LV88-12GC and LV88-03GC are sites of H_2S gas expression, possibly related to hydrothermal vent activities. This observation shows quite clear similarities with previous studies.

3.2.3.2. The relationship between the composition of surface sediment particles and gas characteristics in surface sediments in the southwest sub-basin of the East Vietnam Sea

The evaluation results show almost no correlation between the methane and hydrogen gas composition with the clay and silt and sand grain grades and a weak, almost insignificant correlation between the helium composition and the particles, as mentioned above. The above data show that the relationship between the gas content in the surface sediments in the study area and the grain-sized characteristics of the surface sediments has yet to be found.

3.2.4. The relationship between gases in surface sediments and fault systems in the southwest sub-basin region of the East Vietnam Sea

3.2.4.1. Overview

Previous studies have shown that the gas composition in the bottom sediments and seawater has a close relationship with its origin, and the fault system is considered the main transport channel for these gases from deep structures to the surface of the seabed. Tectonic activities or earthquakes can produce hydrogen and helium anomalies, and magma intrusions can produce hydrogen and carbonic anomalies.

3.2.4.2. Research premises

The expedition of the marine research vessel Akademik Boris Petrov in 2017 identified the 4th zone distributed in the eastern part of the Nam Con Son basin and Tu Chinh - Vung May basin, south of the continental shelf of Vietnam.

According to previous studies, the high methane content in this study area is closely related to the geological structure, which

appears to be typical for methane fluxes from hydrocarbon deposits (Lan Do, Lan Tay, and others) along deep fault zones.

3.2.4.3. The role of the fault system as a conduit of deep-origin gas to seafloor sediments from geochemical evidence

According to the analysis above, the hydrocarbon gases in the surface sediments in the KVPTS and the BTNCS have their origins in favor of biological origin and thermal origins, respectively. The research focus will be on gases in surface sediments distributed in the BTNCS and located in the active area of the 109° meridian fault, along with the Northeast - Southwest fault system. The gas geochemical parameters show a clear role of the fault system on the gas composition in the seabed sediments along the survey area. This study also showed helium and hydrogen anomalies in the surface sediments in this area were also shown. High levels of helium and hydrogen are often associated with deep faults, possibly related to mantle and volcanic activity. Therefore, helium anomalies in surface sediments and bottom waters often identify deep faults.

CHAPTER 4. CHARACTERISTICS OF GAS DISTRIBUTION IN SURFACE SEDIMENTS IN THE SOUTHWEST SUB-BASIN OF THE EAST VIETNAM SEA

4.1. Characteristics of gas distribution in surface sediments in the southwest sub-basin of the East Vietnam Sea

4.1.1. Characteristics of hydrocarbon gases distribution in surface sediments in the southwest sub-basin of the East Vietnam Sea

4.1.1.1. Characteristics of methane distribution in the western East Vietnam Sea according to previous studies

Previous studies have noted the sharp contrast of the dissolved methane content in the bottom water of the western part of the East Sea. Specifically, low concentrations of methane (10-20 nl/l) have been found in deep water areas (500-3800 m). Meanwhile, in the continental shelf areas (30-200 m) and the continental slope (200-500 m), the background value of methane gas increases to 30-40 nl/l.

4.1.1.2. Distribution characteristics of hydrocarbons in surface sediments in the southwest sub-basin of the East Vietnam Sea

Due to the influence of the geological structure, the values of hydrocarbon gas content in the surface sediments have a clear difference between the two areas, namely the BTNCS and the KVPTS. Specifically, the content of hydrocarbons and carbon dioxide in the surface sediments collected at the BTNCS is much higher than that of the KVPTS. In addition, the most noticeable feature is the superiority of the methane composition over other gases such as ethane, ethylene, propane, and butane.

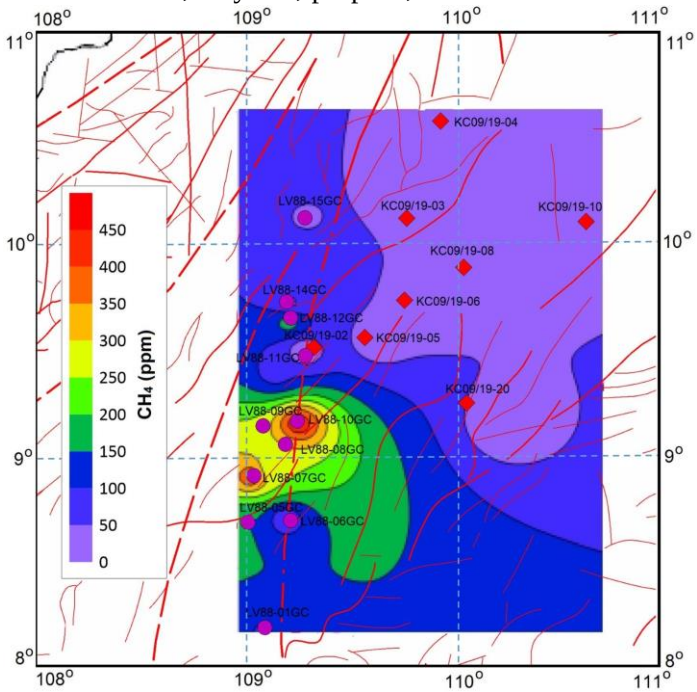

Figure 4.1. Distribution of methane content in surface sediments in the study area

According to the distribution diagram of methane content in surface sediments (Figure 4.1), the methane content decreases markedly from west to east in the study area with increasing water column depth. In BTNCS, methane concentration tends to be highest

in the central area and decreases in both the South and North directions.

Hydrocarbons heavier than methane have a similar distribution pattern to methane, with concentrations in surface sediments decreasing markedly from west to east with increasing water column depth. In the BTNCS, the heavy hydrocarbon gases in the surface sediments with high content are superior to the KVPTS, and the high values are mainly concentrated in the central part of the BTNCS.

4.1.1.3. Threshold, background, and anomalies characteristics of hydrocarbon gases in surface sediments in the southwest sub-basin of the East Vietnam Sea

The values of 2.2 ppm and 103 ppm are the background content of methane gas distributed in the surface sediments at the KVPTS and the BTNCS, respectively. This area exists a large methane emission zone along the continental slope of the BTNCS.

The values of 0.11 ppm and 7.45 ppm can be considered as background content of ethylene gas in the surface sediments at the KVPTS and BTNCS. For ethane, the values of 0.0056 ppm and 24.2 ppm are the background content of ethane in the surface sediments at the KVPTS and the BTNCS, respectively. The background content of propane gas in the surface sediments at the KVPTS and the BTNCS is 0.029 ppm and 5.92 ppm, respectively. Butane gas has two isoforms, butane and i-butane. However, at the KVPTS, these two gases were almost not detected and only found in the BTNCS, with 38.5% and 17.9% of the analyzed samples, respectively. The background content of butane gas in the sediments at BTNCS is 0.625 ppm.

4.1.2. Distribution characteristics of carbon dioxide, hydrogen, and helium in surface sediments in the southwest sub-basin of the East Vietnam Sea

4.1.2.1. Distribution characteristics of carbon dioxide, hydrogen, and helium in surface sediments in the southwest sub-basin of the East Vietnam Sea

Like hydrocarbons, carbon dioxide also tends to decrease significantly from West to East in the study area, from the continental shelf and slope to the deep-water area. The distribution of hydrogen gas in the sediments in the study area does not show the same regularity as hydrocarbons and carbon dioxide. Locations with high hydrogen gas content are scattered in the BTNCS and KVPTS. The helium content in surface sediments generally decreases with the depth of the water column. This varying tendency is quite similar to the law of distribution of hydrocarbon gases.

4.1.2.2. Background, thresholds, and anomalies characteristics of carbon dioxide, hydrogen, and helium in the southwest sub-basin of the East Vietnam Sea

The background, threshold, and anomalous values of carbonic, hydrogen, and helium gases in the study area are also calculated according to the data in two areas, namely BTNCS and KVPTS, to ensure the consistency of geological structure. The values of 0.11 ppm and 1.34 ppm can be considered as the background content of carbon dioxide in the sediments at the KVPTS and the BTNCS, respectively. At KVPTS and BTNCS, hydrogen gas has four points and two hydrogen anomalies in surface sediments, respectively. Values of 7.83 ppm and 9.04 ppm can be considered as background content of hydrogen gas in surface sediments of KVPTS and BTNCS in the study area.

The results of data analysis show that the values of 1.12 ppm and 1.99 ppm can be considered as background content of helium gas

in the surface sediments of the KVPTS and the BTNCS in the study area. One point and two positive anomalies are recorded at these two sequences, respectively.

4.2. Comparison of gas in surface sediments between the study area and the Phu Khanh basin, the Red River basin, and the Gulf of Tonkin area

4.2.1. Comparison of gas characteristics in surface sediments in the southwest sub-basin of the East Vietnam Sea, the Phu Khanh, and Red River basins

Except for carbonic gases, all hydrocarbon gases in the sediments follow the decreasing trend in content from the southwest sub-basin of the East Vietnam Sea to the Phu Khanh sedimentary basin and, finally, the Song Hong (Red River) basin in terms of both maximum and average values. The background concentrations of methane gas in the sediments in the Nam Con Son Basin, Phu Khanh Basin, and Song Hong Basin have values of 103 ppm, 34 ppm, and 26 ppm, respectively.

The distribution characteristics of methane in the surface sediments of the Western East Vietnam Sea region have apparent similarities with the methane in the surface and bottom sea water columns of the Western East Vietnam Sea, according to the R/V Lavrentyev expedition in 2019.

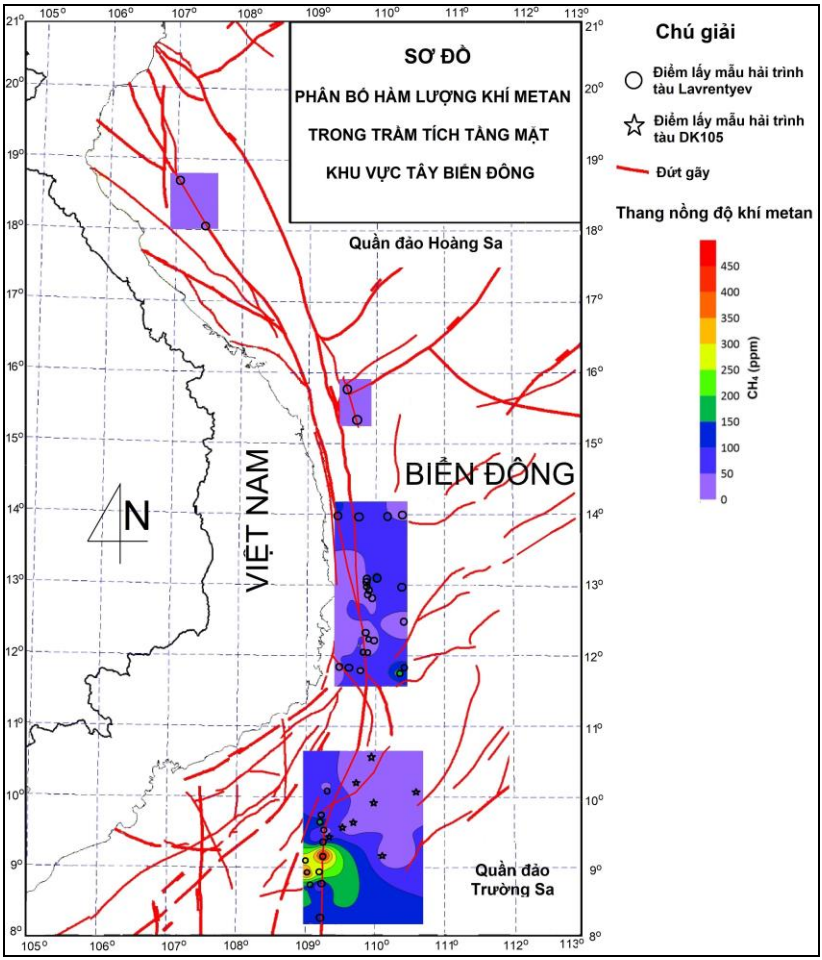

Figure 4.2. Distribution diagram of methane content in surface sediments in gravity cores in the Western East Vietnam Sea

4.2.2. Comparison of gas characteristics in surface sediments in the southwest sub-basin of the East Vietnam Sea and the Gulf of Tonkin

Gas geochemical fields in the Gulf of Tonkin have been studied, showing the average concentrations of hydrocarbons,

helium, and hydrogen along the measured lines. Accordingly, the average content in the measurement routes for methane, ethylene, ethane, propane, and butane gas is 3.98 ppm, 1.12 ppm; 0.18 ppm; 0.1 ppm, and 0.38 ppm, respectively. These values are many times lower when compared to hydrocarbons in sediments in the deep-lying Southwest region of the East Sea in the BTNCS but higher than those in the KVPTS.

Meanwhile, the average hydrogen gas content in the surface sediments in the BTNCS and the KVPTS is higher than in the Gulf of Tonkin. In contrast, the content of helium in surface sediments in the BTNCS and the KVPTS is much lower than in the Gulf of Tonkin.

4.2.3. Comparison of methane in surface sediments between the study area and other seas in the world

The data show that the methane in the surface sediments in both the BTNCS and the KVPTS is significantly smaller than in other western Pacific fringes, such as the Sea of Okhotsk, the Sea of Japan, and the East Siberian Sea, when compared in terms of mean and maximum values. The above sea areas all have substantial methane anomalies, representing large-scale gas emission zones from active fault zones.

CONCLUSION AND RECOMMENDATION

CONCLUSION

1. Gases in the sediments, including hydrocarbons, carbonic, helium, and hydrogen obtained from the Nam Con Son Basin, have higher concentrations than those in the deep southwestern region of the East Vietnam Sea. The difference in geological structure is the leading cause of this disparity.

2. Methane in surface sediments ranges from 0.5 ppm to 440 ppm. The background content of methane gas in the sediments in the Southwest region of the sub-basin of the East Vietnam Sea (KVPTS) and Nam Con Son basin (BTNCS) has values of 2.2 ppm and 103 ppm, respectively. The background content of other hydrocarbon gases such as ethane, ethylene, and propane in the surface sediments of the Nam Con Son basin is many times higher than that in the southwestern sub-basin area of the East Vietnam Sea.

3. The ratios of hydrocarbon gases C1/(C2+C3), C1/C2, C2/C2:1, (C2+C3)/C1 calculated to explain the origin of hydrocarbons in the southwestern sub-basin of the East Vietnam Sea show that hydrocarbon gas in sediment samples in the eastern part of Nam Con Son Basin has a thermal origin. In contrast, the southwestern sub-basin area, it has a mixed origin (thermal origin + biological origin).

4. The thermal origin of hydrocarbons in surface sediments in the Nam Con Son basin has been reinforced by the isotope composition values of δ13C of carbon dioxide and methane.

5. Analysis of the relationship between sediment and gas characteristics in the sediments in the southwestern sub-basin of the East Vietnam Sea showed that at the location of the launch tube LV88-12GC, there were manifestations that could be related to hydrothermal vent activity due to the very high content of Mo, As, Cu and Pb elements compared to other samples.

6. The synthesis of gas geochemical characteristics confirms the deep thermal origin of gas in the study area's seabed sediments in the eastern Nam Con Son basin. The East Vietnam slope fault system (Meridian 109^{o}) and the northeast-southwest fault system are considered the main channels of these gases.

7. The content of hydrocarbons, carbonic, and helium in the surface sediments decreases markedly from west to east with increasing water column depth. This result, together with published data, shows that a large hydrocarbon emission zone exists in the study area. The background content of methane in surface sediments decreases from south to north, specifically in Nam Con Son basin at 103 ppm, Phu Khanh basin at 34 ppm, and Song Hong basin at 26 ppm.

8. Methane in surface sediments in the Nam Con Son basin is higher than in the Gulf of Tonkin; however, compared with the western Pacific fringes such as the Sea of Okhotsk, the Sea of Japan, and the East Siberian Sea, they are markedly lower in mean and maximum values. One of the main reasons is the less active seismic activity in the Western East Vietnam Sea.

RECOMMENDATION

The initial research results of the thesis have the general nature of gas geochemical characteristics in surface sediments in the southwest sub-basin East Vietnam Sea in particular, and in the Western East Vietnam Sea area in general. They are general information about gas geochemical characteristics in surface sediments and their origin in the study area. Therefore, it is necessary to have more detailed studies when conducting oil and gas exploration in each specific area in the study area, especially in the Nam Con Son basin.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1. **Le Duc Luong**, Ryuichi Shinjo, Nguyen Hoang, Renat B. Shakirov, Nadezhda Syrbu (2018). *Spatial variations in dissolved rare earth element concentrations in the East China Sea waters.* Marine Chemistry, No 205, page 1 -15. ISSN: 0304 – 4203. DOI: 10.1016/j.marchem.2018.07.004.
2. **Le Duc Luong**, Renat B. Shakirov, Nguyen Hoang, Ryuichi Shinjo, Anatoly Obzhirov, Nadezhda Syrbu, Maria Shakirova (2019). *Features in REE and methane anomalies distribution in the East China Sea water column: a comparison with the South China Sea*. Water Resources, Vol 46, No 205, page 807 - 816. ISSN: 0097 – 8078. DOI: 10.1134/S0097807819050142.
3. Syrbu Nadezhda, **Le Duc Luong**, Kholmogorov Andrei, Nguyen Hoang, 2021. *Formation of anomalous gas fields of helium and hydrogen in the Cat Ba, Co To and Bach Long Vi islands, northern Vietnam.* Vietnam Journal of Earth Sciences, 43, 3, 301-315. ISSN: 0866-7187. DOI: https://doi.org/10.15625/2615-9783/16197
4. **Le Duc Luong**, Anatoly Obzhirov, Nguyen Hoang, Renat B. Shakirov, Le Duc Anh, Nadezhda Syrbu, Dang Minh Tuan, Nguyen Van Tao, Tran Thi Huong, Do Huy Cuong, Kholmogorov Andrei, Phan Van Binh, Mishukova Olga, A.I. Eskova, 2021. *Distribution of Gases in Bottom sediments of the Southwestern Sub-Basin South China Sea (Bien Dong).* Russian Journal of Pacific Geology, 15, 2, 144-154. ISSN: 1819 – 7140. DOI: 10.1134/S1819714021020044.
5. **Le Duc Luong**, Nguyen Hoang, Ryuichi Shinjo, Renat B. Shakirov, Anatoly Obzhirov, 2021. *Chemical, mineralogical, and physicochemical features of surface saline muds from southwestern sub-basin of the East Vietnam Sea: Implication for new peloids.* Vietnam Journal of Earth Sciences, 43, 4, 496-508. ISSN: 0866-7187.
6. Nguyen Hoang, Shinjo Ryuichi, Tran Thi Huong, **Le Duc Luong**, Le Duc Anh, 2021. *Mantle geodynamics and source domain of the East Vietnam Sea opening-induced volcanism in Vietnam and neighboring regions.* Vietnam Journal of Marine Science and Technology, 21, 4, 393-417.