MINISTRY OF EDUCATION AND TRAINING

VIETNAM ACADEMY OF SCIENCE AND TECHOLOGY

GRADUATE UNIVERSITY OF SCIENCE AND TECHNOLOGY

Topics: CENOZOIC TECTONIC EVOLUTION AND MANTLE DYNAMICS IN THE SOUTH-CENTRAL COASTAL REGION

Major: Geology
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SUMMARY OF DOCTORAL THESIS

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The work was completed at the Graduate University of Science and Technology, Vietnam Academy of Science and Technology

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The thesis will be defended before a University-level doctoral thesis evaluation committee organized at the Graduate University of Science and Technology, Vietnam Academy of Science and Technology at …… on …./…./2023.

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1. The necessity of the topic

The East Vietnam Sea is a marginal sea formed during the Cenozoic period, belonging to the world's largest chain of marginal seas adjacent to the Western Pacific Ocean. With its unique geographical location, tectonic structure, magmatic activity, and evolutionary process, the East Vietnam Sea (EVS) has always attracted the attention of many geoscientists worldwide from many different fields, especially tectonics, magma, geodynamics, mineralogy, and others. Many issues have become the focus of discussion by scientists, of which the most prominent are the formation mechanism, tectonic evolution, and geodynamics. The tectonics in the EVS and its vicinity are closely related to the motion and interaction of the three plates of Indo-Australian, Eurasian, and Pacific Ocean, along with particular forms of energy transmission taking place in the mantle and the surface of the Earth's crust creating the topography of Indochina and the EVS floor today.

The South-Central Coast and adjacent waters are the transitional places of the Indochina microplate to the oceanic crust of the EVS, related to the formation and development of the East Sea, where tectonic activities are most clearly recorded. The East Vietnam Slope Meridian fault zone (EVSMFZ) is the boundary between the Indochina mainland and the East Vietnam Sea basin, formed and transformed in the Cenozoic.

Mantle dynamics, plate motion, geodynamic tectonics, magmatism, and mineralization are always closely related. The linkage and linking processes within the EVS and adjacent continents are still an under-researched issue, especially the issue of assessing the role of mantle dynamics and linking the main tectonic phases of the area needs to be elucidated. Facing these requirements, the Ph.D. student (the student) selected the topic: "Tectonic evolution and mantle dynamics in the Cenozoic in the South-Central Coastal region."

2. The research objective

The thesis aims to study the geological structure, petrographic and geochemical characteristics of basalt formations in the late Cenozoic period in South-Central Vietnam's coastal and offshore areas. The obtained research results allow the graduate student to identify the development stages of tectonic structure, spatial distribution, and geodynamic mechanism. At the same time, clarify the relationship between mantle dynamics, lithospheric plate movement, and regional tectonic activities in the South-Central Coast and adjacent waters.

Scope of detailed study area concentrated in geographic coordinate frame:

108°00' to 112°00' East longitude and

9°00' to 15°00' North latitude, and adjacent areas, including mainland Indochina and the deep basin of the East Vietnam Sea (Figure 1).

3. The aim of the thesis

- Investigating and building a model of tectonic evolution in the East Vietnam Sea and the South-Central Coastal region (Figure 1).
- Defining the relationship between tectonic structure evolution and magmatic activity in the region.
- Determining the source nature and mantle dynamics characteristics of the study area.

4. The tasks of the thesis

1. Research on geological structure characteristics of the continental shelf area of South-Central Vietnam and its vicinity (Fig. 1); characteristics of the main tectonic phases and their roles in forming the geological structure framework of the Earth's crust and the lithosphere in the study area.

2. Study of Miocene-Quaternary basaltic magma's petrographic and geochemical, and related mantle source characteristics, eruption age, and spatial distribution of basalt formation in the study area. The task includes the study of characteristics of chemical composition and morphology of olivine and clinopyroxene phenocrysts in the basalt, major and trace element compositional and isotopic characteristics of basalts, and geochemical characteristics of magmatic melts.

3. Researching and building a model of tectonic evolution in the South-Central Coast according to the relationship between mantle dynamics and regional geodynamic regime.

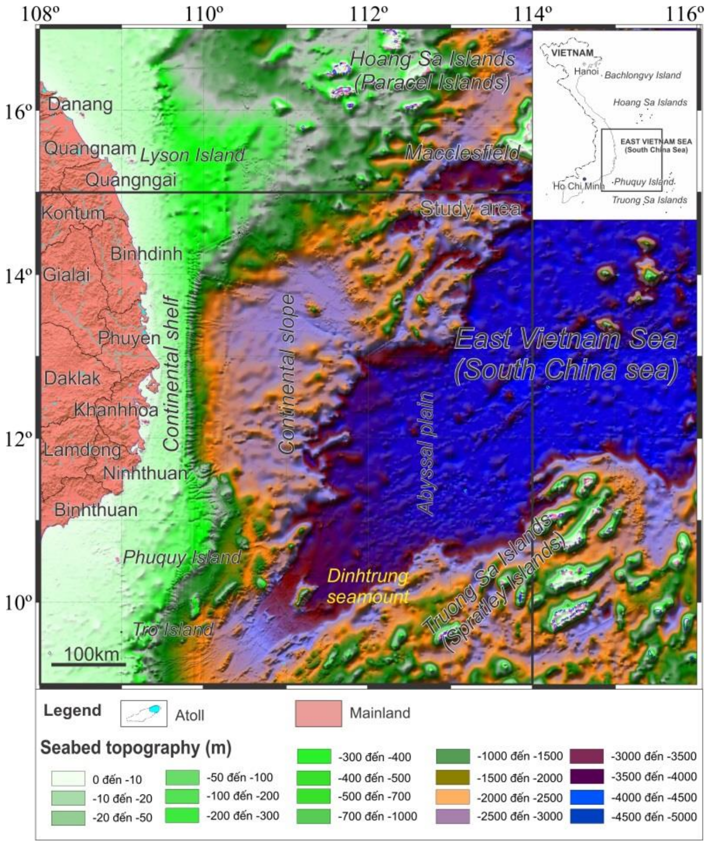

Figure 1: *Location of study area*

5. Defensive argument

Argument 1: The Cenozoic magma-tectonic activities in the study area are divided into six stages, including 1) Before the Middle Eocene (~ 45 Ma), the period prior to the rifting; 2) Middle Eocene – Early Oligocene (45 - 32 Ma), the rifting period; 3) Middle Oligocene - Late Oligocene (32 - 23 million years old), the period of bottom expansion to form the oceanic crust of the East Vietnam Sea in the early stage; 4) Early Miocene (about 23 Ma - 16±0.5 Ma), the period of oceanic crust extension into the continental shelf of Vietnam; 5) Middle Miocene - Pliocene (from 16±0.5 to 5 Ma), the post-extension phase with volcanic eruptions forming the basal cover; 6) Pliocene - Quaternary (from 5 Ma to 0 Ma), the post-extension phase releasing residual energy in the form of monogenic volcanic eruptions.

Argument 2: When the Indian plate collides with Eurasia, microplates and geological structures in Southeast Asia deform and drift above the hot mantle stream, whose temperature is higher than the global mantle average and changing over time. Due to the influence of tectonic activities, the Southeast Asian lithosphere is continuously stretched, slipped, subsided, and thinned; however, the above processes are not enough to generate mantle melting to provide a sufficient amount of forming the oceanic crust in the East Vietnam Sea and Middle Miocene-Quaternary volcanic eruptions in the coastal and the continental shelf region of South-Central Vietnam. The research results of the thesis have proved that the magma mentioned above is formed by activities taking place in the mantle and is reflected through the regional mantle dynamics, which are manifestations of temporal and spatial changes of the mantle flow and the thermal state distributed in the upper mantle, and the characteristics of the magma source (depth, pressure, and partial melting temperature).

6. Discoveries of the thesis

– The research results of the thesis have proved that the deformation and displacement of microplates and geological structures in Southeast Asia and the East Vietnam Sea developed on high-temperature mantle flows, which are unstable in time and space.

– Age data, distribution area, and petrological and geochemical characteristics of basalt have clarified the mechanism of magma formation in the late Cenozoic period in coastal areas on the continental shelf of South-Central Vietnam and the deep-sea basin of the East Vietnam Sea.

– The mantle dynamic mode manifests through time and spatial changes of mantle flow, the change in thermal state in the upper mantle, and magma source characteristics (depth, pressure, and melting temperature) is the driving force that directly affects the tectonic evolution in the study area.

– The graduate student has built a magma-tectonic evolution model in the South-Central Coast and adjacent areas based on geodynamic and mantle dynamic characteristics. The model has shown six stages of tectonic structure evolution, at the same time, explained the close relationship between the events occurring in the mantle and the Earth's crust in the late Cenozoic-late period in the South-Central Coast and adjacent regions.

7. Documentary basis of the thesis

– The graduate student obtained the documents of surveying, measuring, and drawing geological structures and rock samplings along the coast and the continental shelf from Binh Dinh to Ninh Thuan when he was the principal investigator or leading participant of the research projects during the 2012 - 2018 period.

– The set of volcanic rock samples stored at the Far East Geological Institute, Far Eastern branch of the Russian Academy of Sciences, collected on board many research vessels in the East Vietnam Sea in the 1980s, was acquired by the graduate student through international collaboration. The volcanic rock samples were sent for analysis at reputable facilities, including:

– Analysis of the major and trace element composition at the Institute of Geological Sciences, Vietnam Academy of Science and Technology, Geological Survey of Japan, Far East Geological Institute, Far Eastern branch of the Russian Academy of Sciences.

– Analysis of olivine and pyroxene chemical compositions at the Far East Geological Institute, Far Eastern branch of the Russian Academy of Sciences.

– The geophysical data are the products of the national program "Scientific and technological research for the management of seas and islands and marine economic development" coded KC09.02/11-15, KC09.07/16-20, KC09.31/16-20, and KC09.33/16.20.

– Scientific articles related to the content of the thesis, where the graduate student was the primary author or a co-author, published in scientific journals and national and international scientific conferences.

8. The structure of the thesis

The structure of the thesis, in addition to the introduction and conclusion, includes chapters:

- Chapter I. Geological overview of the study area
- Chapter II. Approaches, techniques used and research methods.
- Chapter III. Characteristics of magma, geological structure, and tectonics in the study area
- Chapter IV. Characteristics of mantle dynamics and tectonic evolution of the study area.

CHAPTER I. OVERVIEW OF THE SOUTH-CENTRAL SEA AND NEARBY

1. Geographical location of the study area

The research area of the thesis is on the western edge of the EVS, including continental elements, continental shelf, continental slope, and a part of the deep basin of the East Vietnam Sea (Figure 1). The continental part of the study area is the South-Central Coast; the terrain consists of coastal plains and low mountains (about 200 m above sea level). The plains have a small area because the western mountain ranges spread along the south direction, gradually approaching the sea and gradually narrowing the area. Plains are mainly accreted by rivers and seas, often following the foothills of the mountains. The continental shelf in the Binh Dinh, Phu Yen, Khanh Hoa, and Ninh Thuan provinces (from latitude 11048' to 14000' north latitude) has a narrow width, averaging about 40 km. The most expansive place is 60km (in Binh Dinh province), and the narrowest is 20km (in Deo Ca, Phu Yen). On the topographic map, the isobaric depth of -200m of water is the natural boundary of the continental shelf in this area. Out of this boundary to the east, the depth of the seabed increases suddenly from -200m to -2500m, creating a cliff that is visible on the terrain. To the south of latitude 11048'N, the continental shelf changes in a northeast-southwest direction and expands rapidly with a width of about 200km. The continental slope has a depth ranging from -2500 m - -3500 m, which tends to expand in contrast to the continental shelf. The northern part is expanded, and the most expansive place is over 300km in Binh Dinh province. The deep valley of the East Vietnam Sea has a relatively flat terrain, with a depth ranging from -3500m - -5000m. The terrain tends to narrow to the southwest when entering the continental shelf of Vietnam. Here appears an underground mountain range over 1000m high, along the axis of the terrain concave and ends at Dinh Trung seamount. This seamount creates a natural boundary between the two regions of the Northeast and the Southwest: in the southwest, the terrain of the seabed is more rugged and differentiated, and in the northeast, the seabed is gradually stabilized, with a relatively flat surface, moving into the deep-water depression of the East Vietnam Sea with oceanic crust.

2. The tectonic position of the study area on the regional tectonic structure framework

The geological structure of the South-Central Coast and adjacent sea areas results from a complex movement and evolution of tectonic plates in the Asia and Pacific regions. The focus of the tectonic evolution processes in the Cenozoic period of Southeast Asia is the left-strike slip activity of the regional fault system, NW-SE direction, and the formation of oceanic crust spreading in the East Vietnam Sea.

The Cenozoic oceanic crust of the EVS was formed on the one hand, leading to the subsidence and breakup of a large part of the edge of the Asian continent (such as the Truong Sa and Hoang Sa archipelagos); on the other hand, it split and pushed some continental fragments southeastward and attached to the chain of islands there (Northern Palawan block), forming the outer island chain, separating the EVS from the Pacific Ocean plate. The tectonic context of the EVS is fundamentally different at the North, South, West, and East coasts, including a passive edge in the north, an active converging edge in the east, a normal slip in the west, and a southern edge -a large area combining the thinned drifting crust plates of Truong Sa - Tu Chinh - Vung May and the ancient Borneo - Palawan subduction zone in front.

The West of the EVS is a narrow continental margin with a complex structure containing the East Vietnam Slope Cliff (EVSC) slipping zone. At the last stage of the EVS formation, the fault of the EVSC has acted as a tectonic relay, adjusting the tensile stress of the western part of the East Vietnam Sea (Hayes and Nissen, 2005). This activity causes the western continental margin to have a normal slip dynamic and create strong subsidence, making the continental shelf very narrow, but the continental slope is quite broad, and the terrain is complex. In particular, the normal and horizontal sliding has made the Earth's crust stretch and thin (Savva et al., 2016). The structural units of the study area are developed based on three crustal regions of the Earth: 1) continental crust domain, 2) transition crust domain, and 3) oceanic crust domain.

3. Overview of geology and tectonics in the Cenozoic period

As mentioned, the focus of the tectonic evolution processes in the Cenozoic period of Southeast Asia is the left-lateral strike activity of the NW-SE fault system and the formation of crustal extension of the East Vietnam Sea. The study area belongs to the eastern edge of the Indochina block and the western edge of the EVS, closely related to the movement processes of the Indochina block along with the opening of the East Sea with volcanic activities taking place in the Eocene - Quaternary period. Synthesis of research results of geology, tectonics, geodynamics, petrology, and magma from many published works shows that the main tectonic events taking place in the study area over time include (Fig. 2):

(1) The collision of the Indian plate with the Eurasian plate began about 50 - 45 million years ago.

(2) The process of clockwise displacement and rotation of the Indochina block, accompanied by the spreading process on a large scale in the western continental shelf of the EVS, took place about 45 – 23 million years ago.

(3) The process of stretching the Earth's crust to form the oceanic crust of the EVS during the period 33 to 16±0.5 million years ago.

(4) Volcanic activities took place in the South-Central region, on the continental shelf and deep basins of the EVS during the Middle Oligocene - Quaternary period, and the activity of the Manila subduction zone in the eastern EVS.

(5) The activity of the Borneo-Palawan subduction zone in the southern EVS.

Corresponding to each tectonic event, the South-Central Coast continental shelf is characterized by different sedimentary layers, separated above and below by distinct regional unconformities. Documents explaining seismic sections from published works in the study area have identified seismic-stratigraphic boundaries and their morphological features. The obtained results have identified 5 nonconforming surfaces (S1 - S5) and 6 structural layers (T1 - T6) in the study area; 5 incongruent boundary surfaces including:

- The S1 boundary (acoustic or crystalline foundation) is the dividing boundary between the upper Cenozoic sedimentary formations and the lower pre-Cenozoic formations. The S1 surface is at the bottom of the Oligocene age sedimentary layer (about 36 Ma).

– The S2 boundary is the top of the Oligocene or the erosive bottom surface (BU-Break up Unconformity), with an age of about 30 million years. In the Deep Depression of the East Sea, where the oceanic crust is located, the surface of S2.

– The boundary S3 is the surface of the lower Miocene roof, with an age of about 15.5 Ma, also known as MMU (Middle Miocene Unconformity). Surface S3 is a boundary marking the transition from active tectonic to resting mode.

– The S4 boundary is the surface of the middle Miocene roof about 10.4 million years ago. The surface of S4 marks the period of sea recession, which is regional.

– The S5 boundary is the upper Miocene roof, aged about 5.2 million years. The S5 surface is an intense and prolonged erosion surface, causing the ancient terrain surface to be regionally flattened over most sedimentary basins.

Interspersed between the 5 boundary surfaces are five structural layers (or sedimentary spans) as follows:

– T1 layer = Eocene – Oligocene is sandwiched between S1 and S2.

– T2 layer = Lower Miocene, sandwiched between S2 and S3.

– T3 layer = Middle Miocene, sandwiched between S3 and S4.

– T4 layer = Upper Miocene, sandwiched between S4 and S5.

– T5 layer = Pliocene - Quaternary, sandwiched between S5 and the seabed.

The T1 and T2 horizons are considered co-spreading (syn-rifting) and the T3-T5 sets are post-rifting sediments.

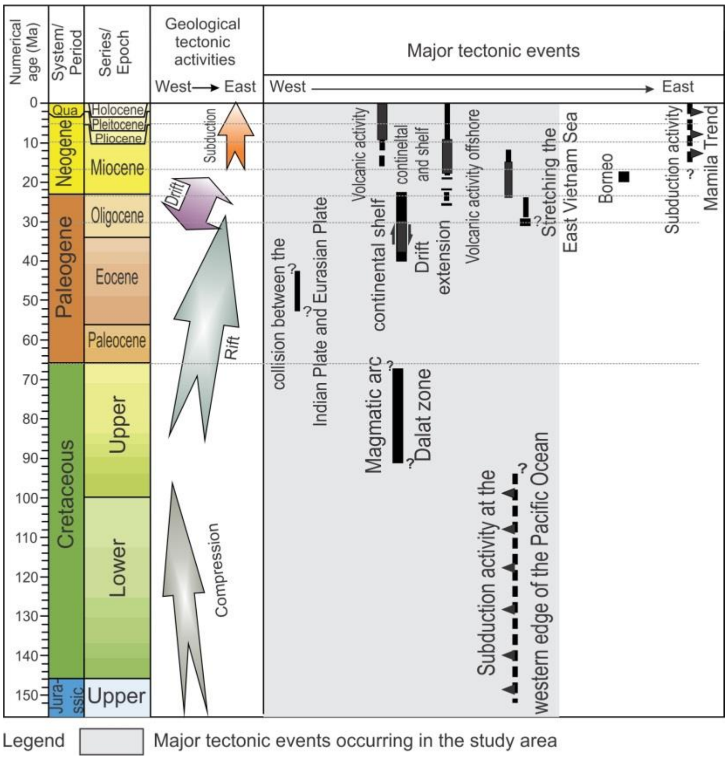

Figure 2. *Summary of major tectonic events taking place in Southeast Asia in the Late Mesozoic – Cenozoic period (after Briais et al., 1993; Li et al., 2015; Savva et al., 2016; Tapponnier et al., 1982, 1986; Taylor and Hayes., 1983, Franke et al., 2013)*

In the tectonic context, magmatic activity was recorded mainly in the late Cenozoic period related to major tectonic events, including: 1) Magma activity in the deep-sea basins of the East Vietnam Sea and the neighboring continental shelf regions of the Oligocene - Miocene (early - middle) period related to the formation of the oceanic crust of the EVS; 2) Volcanic activity on the continental shelf and along the South-Central Coast extending from the Miocene (middle) to Quaternary related to the mantle lateral flows that were extruded and spread following the collision between Indian and Eurasian plates (Flower et al., 1992; 1998; Hoang et al., 1996, 2013; Lee et al., 1998; Hoang and Flower, 1998; Pham Tich Xuan and N. Hoang, 2002; Nguyen Hoang and Phan Trong Trinh, 2009; An et al., 2016). In the Oligocene - Miocene (early - middle) period, magmatic activity occurred sporadically in some places on the northern continental shelf of the EVS. Magma activity was the operating mechanism forming the oceanic crust and was divided into periods corresponding to the development stages of the EVS from 32 to 16±0.5 million years ago. During the Middle Miocene-Quaternary period, monogenic volcanism occurred strongly along the EVS spreading axis, in the North, West and South of the EVS continental shelves and nearby. Although volcanic activity is well-spread, the amount of magma brought to the surface is not large enough to form an igneous province.

4. Formation and evolution of the East Vietnam Sea

The East Vietnam Sea is a sub-ocean with a full range of complex and spatially unstable structural components, with drastic location and extension rate changes over time. According to time and evolutionary characteristics, the East Sea basin is conventionally classified into three sub-basins: Northwest, East, and Southwest. According to anomalous documents from (Briais et al., 1993), the EVS was formed from 33 to 16±0.5 Ma. From 16±0.5 Ma up to now, the East Sea basin has been passive and is gradually shrinking due to a part in the east being subducted and disappearing under the islands of the Philippines along the Manila canyon.

Currently, there are several Cenozoic tectonic models. The regional tectonic models mainly focus on solving the dynamic relationship of the plates, the direction of displacement of the NW-SE, sub-meridional faults, and their role in the evolution of the oceanic crust of the East Vietnam Sea in the Cenozoic. Models include:

- The first model follows the models of the authors Tapponnier et al. (1982, 1986), Leloup et al. (2001), and many other published works suggest that, in the early stage of the New tectonics (starting from the Eocene), the Indochinese tectonic plate moved towards the SE, creating a strong left-lateral trike slip of the oriental fault system of NW - SE, primarily, the Red River fault. Accordingly, Tapponnier and colleagues (1982, 1986) considered it the main driving force for the formation of the oceanic crust of the EVS.

- The second model by Holloway (1981), Taylor and Hayes (1983), and Hall (2002) suggested that the formation of oceanic crust in the East Vietnam Sea was associated with the process of subduction of ancient (Mesozoic) oceanic crust at the Palawan Trench. According to the authors, traction generated by the subduction of the ancient (Mesozoic) oceanic crust under the Borneo block might contribute to the oceanic crust formation in the EVS in the early stages.

- The third model follows a group of other scientists, such as Rangin et al. (1995a), Le Pichon et al. (1995), Roques et al. (1997), and Huchon et al. (1994) has an intermediate view. On the one hand, they confirmed the strong left-strike slip kinetic pattern of the NW-SE faults and suggested that this system played a breakthrough role in spreading the EVS's oceanic crust. On the other hand, in the later period (after the magnetic anomaly No. 7), the East Vietnam Slope Cliff fault has a right-slip pattern in the context of the wedge-shaped oceanic crust moving towards the Southwest.

- The marginal sea opening model of some Vietnamese authors based on the research results of the Red River fault zone: a group of Vietnamese scientists has proposed a kinetic model of the movement of the Indochina block rotating clockwise with three centers of rotation and corresponds to the two EVS open phases (N.V Vuong et al., 2004).

- Synthetic results of the EVS formation according to the discoveries of the International Ocean Discovery Project 349 (IODP 349): scientists from many countries worldwide conducted drilling at many locations in the deep waters (deep basins of the EVS) and its northern continental shelf. The results show that the East Vietnam Sea was formed in the Paleocene - Eocene period.

5. Relationship between mantle flows and Asian lithosphere deformation

Some studies on Asian tectonic evolution suggest that the collision of the Indian plate with the Eurasian plate has deformed the Asian lithosphere at a regional scale, extending from the Himalayas to the Pacific Ocean and forming some subduction zones (Tapponnier et al., 1982, 2001; Kimura and Tamaki, 1986; Jolivet et al., 1994; Royden et al., 2008). Geodynamic studies have shown that the collision activity caused the Indian plate to continuously move northward more than 3000km between ~50 Ma and ~30 Ma, strongly affecting the lithosphere (Dewey et al., 1989; Tapponnier et al., 1990; van Hinsbergen et al., 2011; Bouilhol et al., 2013). This process gradually weakened about 30 million years ago and was replaced by continental blocks' extrusion (escape) along major faults, such as the Ailao-Shan Red River, Tien Shan, and Altyntagh. The Indochina Block extruded (escaped) to the southeast. The asymmetrical strain distribution between the NE and NW parts of the colliding zone is explained by the concept of a free boundary along the eastern edge of Asia that allows the Indian plate to extend further into Asia (Jolivet et al., 1990; Kimura and Tamaki, 1986; Tapponnier et al., 1982). Some scientists have suggested that gravity also plays a role in the regional tectonic context and that the Asian lithosphere is gravitationally unstable by itself (Davy and Cobbold, 1988; Jolivet et al., 1990; Fournier et al., 2004). According to Jolivet et al. (2018), the cause of the instability is due to the displacement of the mantle flows, which strongly dominate the lithosphere deformation activities. As the mantle flows, there can be longitudinal effects in addition to the horizontal displacement (Bird, 1998; Jolivet et al., 2018). The deformation caused by the mantle flow effect appears at locations where there is a sudden change in the depth of the surface of the lithosphere boundary and the asthenosphere (LAB) and leaves signs of intraplate deformation on the surface of the crust (Conrad and Lithgow-Bertelloni, 2006; Koptev et al., 2015).

Based on geological, geophysical, and remote sensing data, the authors Jolivet et al. (2018) suggested that the direction and direction of displacement of the Indian and Eurasian plates in a long cycle (about 50 million years) are similar corresponding to the direction and direction of the deep mantle current (about 200km) originating from the Indian Ocean, moving from the southwest northeast to the Sea of Japan (Figure 3b, d). Besides, there exists a high-temperature anomalous mantle stream (>1300^{0}C) at shallower depths (about 100km) with complex dimensions. In Figure 3 a, b, c, it is observed that the shallow mantle current (100km depth) starting from the Indian Ocean moves southwest northeast and is deflected in the sub-latitude direction due to the hindrance of the Indian plate. The degree is subducted below the Eurasian plate. At the northeastern edge of the impact zone, the shallow mantle changed clockwise and shifted toward Southeast Asia in a sub-meridian direction. It can be seen that the displacement of the shallow mantle flow is related to 4 main factors, including 1) the impediment to the displacement of the subduction zone at the colliding zone; 2) stretched and thinned lithosphere in Southeast Asia (Figure 3a); 3) sudden change in the depth of the LAB transition zone surface; 4) the Indochina block displacement during the Late Cenozoic (the flow movement is about 0-200 deviated from the plate moving direction (Figure 3d).

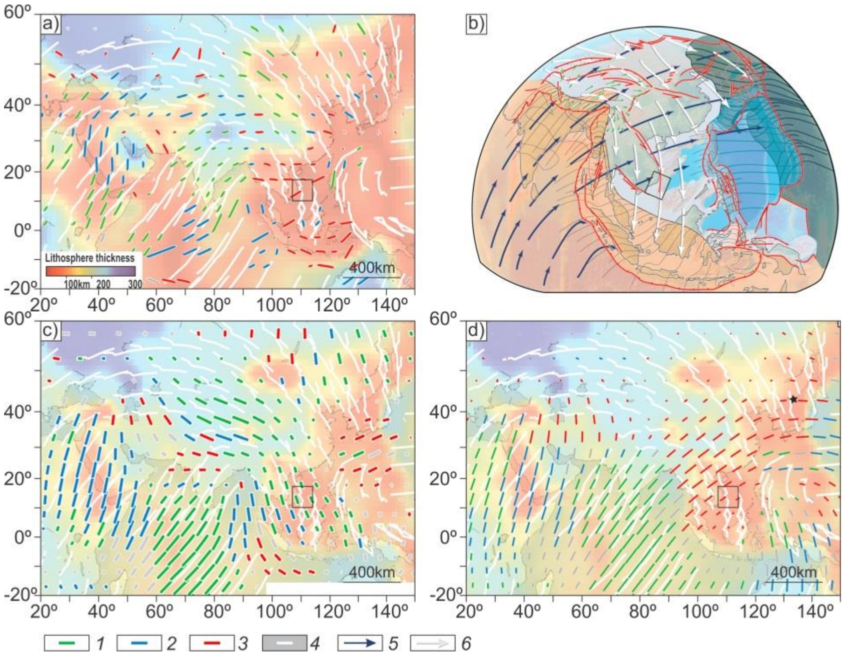

Figure 3. *Scheme of mantle flow motion and India-Eurasia plate displacement; a) Sketch illustrating Asian lithosphere thickness and plate displacement in a long period (50 million years); b) Movement of mantle flows at depths of 200km and 100km; c) relationship between the direction of mantle flow displacement and plate displacement at a depth of 100km; d) relationship between the direction of mantle flow movement and plate displacement at a depth of 200km (after Jolivet et al., 2018).*

Simultaneously combining the results of calculating the lithosphere thickness, the trend of mantle displacement at depths of 200km and 100km, and the displacement of the Earth's crust over a long period can be seen as high compatibility between the deep mantle flow (200km) with the extrusion trend of the Indian plate in a long cycle. On the other hand, the shallow mantle flow (100km) tends to be firmly compatible with the displacement of the Indochina-thinned lithosphere. Although the role of mantle currents in the opening of the marginal sea (for example, the Sea of Japan and the East Vietnam Sea) is still being studied; however, the time lag when the plate collision occurred (50 million years ago) and the volcanism in Southeast Asia (after 15 million years ago and the strongest after 8-10 million years ago) are pretty consistent with the distance the mantle flows (about 1700km) with a speed of 5cm/year according to Jolivet et al. (2018). The movement of shallow mantle flows and deformation of the Earth's crust in

Indochina have caused significant changes in the South-Central continental shelf area. Especially in the middle Miocene period (about 16-17 million years ago), the Phu Khanh sedimentary basin started an intense subsidence process, causing the sedimentary environment to completely change from a shallow marine environment to a deep-sea environment (Fyhn et al., 2009b).

6. Remaining problems

– While summarizing the research results, the graduate student found some existing problems have emerged, and the resolution of these shortcomings is also the thesis's research contents and primary objectives, in detail as follows:

– Was the formation mechanism of late Cenozoic magma generation arising from lithosphere extension or by the arrival of high-temperature mantle flows?

– What was the nature of mantle dynamics in the study area during the Cenozoic period?

– What is the role of mantle dynamics on the regional tectonic structure framework?

CHAPTER II. THEORETICAL BASIS AND RESEARCH METHODS

1. Theoretical basis

Plate tectonics is a scientific theory that explains the nature of the formation and evolution of the lithosphere, creating the major landforms on the Earth's surface. This theory was first invented by German scientist Alfred Wegener in the early 20th century, with the idea of "continent drifting," but it was later forgotten. New independent discoveries concerning the Earth revived the theory in the early 1960s: paleomagnetism, mid-ocean ridge topography, and the distribution of earthquake epicenters worldwide. The invention of plate tectonics theory is considered one of humanity's ten most significant inventions in the 20th century.

From the point of view of plate tectonics, the major topographical manifestations observed on the Earth's surface are the result of the displacements and interactions between the large plates of the uppermost part of the Earth's crust (the lithosphere). The leading cause of the whole process arises due to thermal convection dynamics within the mantle.

Kinetics is a branch of mechanical physics that studies the motion of objects and their relationship to interactions between objects. Kinetics is concerned with the cause of the motion of objects, which is Force. Mantle dynamics can be seen as the scientific field of study of dynamics arising in the mantle to find out what causes the motion of the lithosphere. With this view, mantle dynamics are the leading cause of plate shifts; therefore, when studying the tectonic evolution of a particular region, two factors need to be considered: 1) the mantle dynamics regime in each period when the plate movement occurs, and 2) the displacement of the structural blocks. Combining these two factors allows us to build a quantitative (theoretical) model of the tectonic evolutionary history of a research area.

2. Mantle dynamics study

2.1. The mantle

The mantle is the largest body of matter inside the Earth (82% of total volume and 65% of total mass). Mantle makes up nearly all of the Earth's silicates, the chemical composition of which is directly reflected in deep-seated peridotites brought to the surface through kimberlite pipes or alkaline basalt eruptions. In the vertical section cutting through the center of the Earth, the mantle has a boundary extending from the bottom of the crust (accounting for 0.6% of the silicate mass) to the upper surface of the outer core (at a depth of 2,900 km). In addition, the chemical composition of the upper mantle is shown indirectly through the geochemical characteristics of basaltic rock types (MORB: mid-ocean ridge basalt, OIB: oceanic island basalt, IAB: island arc basalt, and more). The geochemical evidence of basalt in different regions in different tectonic environments worldwide shows the chemical heterogeneity of the mantle. The chemical heterogeneity was created by differentiation and material evolution following the formation of the crust from a primordial mantle about 3 billion years ago. The mantle chemical heterogeneity is also formed by crustal material being brought down to the mantle at subduction zones or by erosion of the lithosphere base (keel) and rolling down the mantle under the action of convection currents. Studies of mantle's chemical and isotopic heterogeneity suggest that they may exist over a large scale, such as isotopic heterogeneity beneath the South Pacific or Indian Oceans; sometimes chemical anomalies exist only within the region, for example, geochemical anomalies and lead isotopes below the East China mantle.

2.2. Primitive melt

Mantle material (plagioclase-, spinel-, or garnet- peridotite depending on the melting depth) can be heated to form basaltic melts due to physicochemical changes that cause an imbalance in the material such as a decrease in pressure (decompressed melting), increase in temperature (thermal melting), and decrease in temperature under the effect of volatiles (for example, pressurized water, termed as hydrous fluid). The first may be due to lithosphere rifting (e.g., melting below the mid-ocean spreading axis). The second case may be due to the input of heat sources rising from the depths of the mantle, such as mantle plumes or hotspots. The third case is the mantle melting in subduction zones under the influence of pressurized fluids (water, CO2...) released by hydrous minerals from the subducted oceanic crust to the mantle.

The generated meld is segregated from the host rock environment due to its lower density and aggregated until the volume is large enough to be pushed to the surface by gravity. After melting, the residual rock is also raised because the density is lower than the host rock. These remnants gradually pile up to form the lithospheric mantle. Mechanically, the lithosphere mantle is much cooler, drier, and less elastic than the underlying mantle (or asthenosphere), making it more difficult to melt.

According to experimental petrographic data, the molten composition of primitive mantle material (which is an ultramafic rock that has not undergone melting) has a magnesium index (Mg# = 100x[(Mg^{2+} + Fe^{2+})/Mg^{2+}] from 68 to 70, and the magnesium index of the corresponding mineral olivine (referred to as forsterite composition: Fo) with the above solution is in the range of 88 to 90, calculated by the Fe-Mn elemental distribution coefficient between the olivine and the solution. (KD = (FeO/MgO)ol/(FeO/MgO)liq) = 0.30. The melt on the way to the surface can stay in some intermediate magma chambers and gradually reduce the temperature, leading to fractional crystallization, mainly olivine, followed by olivine ±clinopyroxene and ±plagioclase.

2.3. Primitive Magma

Basalt with a magnesium index close to the abovementioned parameters can be considered quasi-primitive. Basalts with such magnesium content can approach their original melt composition through simple math. Assuming that the basalt samples under study only undergo fractional crystallization of olivine [(Mg,Fe)2SiO4], it is possible to compensate for the olivine removed from the system by compensating them with little increments (about 0.1% - 1%) until either the forsterite composition of olivine is 88-90%, or the magnesium index of basalt (melt) is 68-70. In this way, with some geochemical conditions, one can approach the primordial composition of basalt with a relatively higher MgO composition, i.e., near primitive, less prone to strongly fractional crystallization.

Experimental petrography also shows that the major element chemical composition of the primordial melt is a function of melting pressure and temperature. In addition, the trace element chemical composition of the melt is a function of the partial melting percent and is strongly correlated with the nature of the mantle source material. That is, through the geochemical composition of the melt, one can reproduce the nature of the mantle material source and its melting parameters, such as pressure, temperature, and melting degree (percentage).

2.4. P-T balance and mantle dynamics

The rate at which temperature increases with depth is called the geothermal gradient and represents the relationship between temperature and pressure (depth). The average geothermal gradient over 100 km from the crust is about 25°C per km of depth.

The temperature-pressure (depth) diagram illustrates the relationship between the geothermal gradient (red line) and the onset of the mantle solid state transition (solidus, green line). The geothermal gradient varies with depth passing through the Earth's crust into the upper mantle. The area to the left of the green line of solid mantle matter (solidus) to the right is where the formation of liquid components (liquidus) begins (Figure 4). As the temperature and depth increase at about 125km, the natural geothermal gradient point position is closest to the solidus line. The solidus curve tends to slope to the right because the melting point of any substance depends on pressure. The higher pressure created at a greater depth increases the temperature required for melting.

The bottom of the Earth's crust has a depth of about 35km and a pressure of about 10,000 bar (1Gpa). The temperature at a depth of 100 km is about 1200°C. At this temperature and pressure, the bottom of the crust and mantle is solid (the mantle has not yet appeared to melt). This state continues at a depth of 150 km; the geothermal ramp is to the left of the solidus line. This relationship continues through the lower mantle to the mantle-core boundary at a depth of about 2900 km.

Studies have shown three ways the Earth's natural geothermal line intersects and crosses the solidus line: 1) the mantle appears to be partially melted due to decompression; 2) the mantle appears to be partially melted due to the addition of volatiles; and 3) increase in mantle temperature due to migration of hot mantle flows.

Under normal conditions (case 1), the geothermal line does not intersect the solidus line beneath a stable plate, so no melting occurs. In the other four cases, the geothermal line slope is shifted to the right and intersects the solidus line simultaneously, causing the mantle to melt. In different tectonic contexts, the depth of intersection between the geothermal line and the solidus line is also different, which means a mechanical difference in the melt formation in the mantle. Case 2 represents the melt generation due to the input of a thermal source to the upper mantle. Case 3 represents the melt formation due to decompression. Case 4 represents the melting due to mantle heat supplied by convection currents originating from the core (mantle plume), and case 5 represents the melting due to the addition of fluids released from the subducted plate. In the 5th case, the geothermal line remains the same while the solidus equilibrium line tends to shift to the left, which means that when the mantle is supplemented with volatile compounds, mantle melting may occur easier.

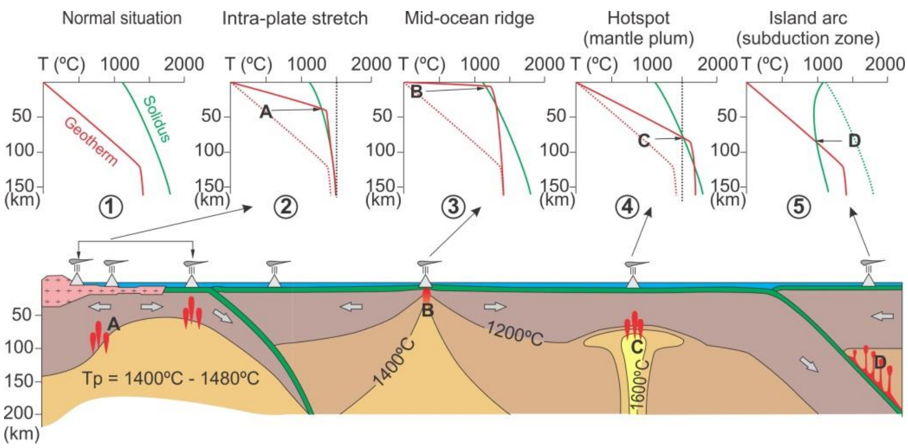

Figure 4. *Simplified scheme showing each relationship between temperature and depth of natural geothermal line (red line) and mantle transition from solid (solidus) to liquid (liquidus)) (green line) in different tectonic environments.*

The petrographic and geochemical composition analysis results, when posted on the normative charts, allow us to identify the transformation processes taking place in the mantle. We can determine the physical parameters that allow the reconstruction of the evolutionary context based on the P-T parameter calculations according to the plate tectonics theory. Thus, to build the tectonic context of a research area, we can rely on the material composition formed directly in the mantle or through modified intermediate magmatic products. On the other hand, we can convert a basalt to a primitive mantle state based on its chemical composition.

3. Studying the displacement of structural blocks

A structural block is created from combinations of litho-tectonic associations of different origins but structured in the same space and formed in similar tectonic contexts. Usually, the structural blocks are separated from each other by deep faults. The tectonic lithology in a structural block with similar deformation characteristics is called a sub-block.

The deformation of rocks is a change in their shape, sometimes in volume and material composition. Deformed rocks can be caused by external forces (tectonic forces) and/or temperature changes, and mineral facies. When rocks are deformed, the elements that make them up are displaced and change their shape from the original. An area may be affected by one or more different deformation phases. In the multi-phase impact area, the structures become more complex, overlapping the late architectural elements on the early-formed structures is common.

A strike-slip zone is a surface structure formed by deformations developed at different depths in the crust. The predominant deformation mode to create these zones is shear strain, which causes the rocks in the flanks of the two zones to be displaced relative to each other in opposite directions in the direction parallel to the boundary of the zone. Sliding zones are usually relatively narrow, with near-parallel boundaries between rock bodies that are less deformed and have a heterogeneous internal structure. Discontinuous shear zones or surfaces can connect to create high-density deformation zones surrounding rocks with lower degrees of deformation.

Based on the deformation characteristics of the rock along the depth of a shear zone, it can be classified into the following types: the brittle shear zone, plastic shear zone, and intermediate, brittle-plastic shear zone.

Deformation processes form deformed structures; such structures often differ from the original structure, which are structures formed during the deposition of materials to create sedimentary rocks (layered structure, co-sedimentary structure, unconformity, sedimentary copper split fiber, sedimentary copper bending, sedimentary copper fault), eruption and intrusive structure (flow structure of igneous rock, intrusion boundary). Structures created by deformation usually include folds, faults, surface structures (plate structure, cracks, sliding surface), and line structures (wrinkled grain lines, lines of mineral tension, and elongation).

Each deformed phase usually produces a generation of structures with specific characteristics. A structure generation is a collection of structures formed in the same period and under the influence of the same stress field. In a phase, deformation may include one or more generations of conformation. A tectonic event consists of one or more deformed phases of related origin and time. The conformation generations define a deformation event usually formed in a specific time sequence. Thus, to divide the deformation phases, it is necessary to identify the structural generations and link them to determine the tectonic phases. We can determine the tectonic events in the study area by linking the tectonic phases.

We can use two ways to determine the age of tectonic events: 1) Determine the relative age and 2) Determine the absolute age. However, not every tectonic event can identify the two methods simultaneously. It is necessary to rely on geological formations and structures formed in that period o determine the age of tectonic events for a specific region.

4. Group of techniques used to carry out the thesis.

- Collecting and analyzing data.
- Technical team to investigate, survey, measure, and collect samples.
- Processing analytical samples.

5. Research methods

The student uses several physical tectonic methods commonly used in Vietnam, such as statistical fracture (crack) methods introduced by Seminsky (2014, 2015) and Delvaux and Sperner (2003), to determine stress fields in the geological research for the thesis.

The rock-forming minerals were determined using a polarizing microscope. The analysis gives information about rock-forming mineral compositions, secondary minerals, and textures and structures of rocks.

The calculation of primitive magma compositions and determination of the related temperature and pressure conditions followed previous studies (Yamashita et al., 1996; Hoang and Flower, 1998). The method is to convert the major oxide component of basalt to the original one by adding a certain amount of olivine until the computed magmatic melt reaches an equilibrium with the mineral composition of unfractionated olivine. During the implementation of the thesis, the graduate student has updated and added new approaches to suit the petrographic and geochemical characteristics of basalt in the study area. Additional updated content and results are presented in detail in 4 articles, of which the student is the first author.

CHAPTER III. MAGMA CHARACTERISTICS, GEOLOGICAL STRUCTURE AND TECTONICS OF THE STUDY AREA

1. Late Cenozoic magmatic activity in the study area

1.1. Distribution area, age of basalt formation in the Miocene - Quaternary period

Volcanic magmatic activity in Southeast Asia took place strongly during the Miocene - Quaternary period. Among the basalt areas, Vietnam and Hainan Island are two volcanic areas with the most extensive distribution and volume. In the deep basins of the East Vietnam Sea, volcanic eruptions formed the oceanic crust and appeared along the spreading axis continuously until the sea opening process ended. The results of linking age data, distribution of basalt formations, main tectonic events, and magma activity in the study area and vicinity are summarized as follows:

The syn-East Vietnam Sea opening volcanism (33 to 16±0.5 million years ago) formed the deep-basin oceanic crust and monogenic volcanoes distributed along the spreading axis.

The post-East Vietnam Sea spreading (<16 million years- now) volcanic eruptions scattered along and around the spreading axis, distributed in most sub-basins of the South-Central continental shelf and vicinity. The results of isotopic ages and seismic data of the continental shelf show that they appear in three main stages, including:

– The period from 15.5 to 8.5 Ma: eruptions appeared along the coast of Quang Ngai (about 12-7 Ma) and Phu Yen (10-9 Ma) provinces related to the formation of the voluminous basalt plateaus in South-Central Vietnam.

– From 7.5 to 4.5 Ma: volcanic eruptions appeared in Quang Nam, Quang Ngai, and Binh Thuan provinces. The magmatic activity of this period has a transitional form; the eruption was fissure, forming basaltic covers of various thicknesses, but the cover scale is relatively small.

– From 3 to 0 million years ago: monogenic volcanic eruptions happened in Quang Ngai province (Ba Lang An - Binh Chau, Ly Son Island), Binh Thuan (Hon Lan), and Ba Ria - Vung Tau province (in Dat Do district).

1.2. Basalt geochemical characteristics

1.2.1. Classification of basalts in the study area

Basalts are classified based on the correlation of silicon oxide (SiO_2) and total alkali ($Na_2O + K_2O$) content (according to Le Bas et al., 1986). On the classification chart, they lie on either side of the alkaline and sub-alkaline/tholeiite division (Figure 5). The SiO_2 content varied from 41.97 to 57.58 wt%, corresponding to total alkalinity (Na_2O+K_2O) ranging from 2.5% to 10.81 wt%.

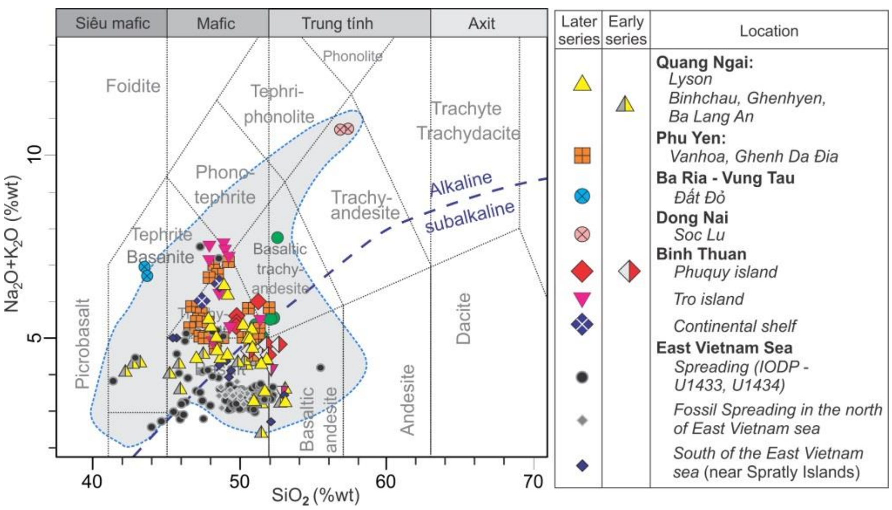

Figure 5: *TAS chart of basalt classification based on total alkalinity (Na2O+K2O) and SiO2 correlation according to Le Bas et al. (1986). The data are of the thesis and published works.*

Basalt of period 15.5 to 8.5 Ma in Phu Yen province includes in Song Cau commune (9 Ma) with high total alkalinity (5-7 wt%), SiO_2 = 49-51 wt%, distributed in the alkaline basalt field; other areas such as Van Hoa, Ghenh Da Dia, and Cung Son distribute to two sides of the alkaline and sub-alkaline division line.

Basalt in the 7.5 to 4.5 Ma period in Quang Ngai (Binh Chau, Binh Son, Ba Lang An, Sa Ky) was mainly distributed on both sides of the line dividing the alkaline and sub-alkaline/tholeiite basalt fields.

Basalt of stage 3 to 0 Ma occurs in Ly Son Island (Quang Ngai province), Dong Nai (Soc Lu, Thong Nhat), Binh Thuan (Hon Lan, Phu Quy, and Hon Tro), and Ba Ria - Vung Tau (Dat Do, and continental shelf) is distributed in both alkaline and sub-alkaline fields.

1.2.2. Characteristics of the elemental geochemistry of basalt

The major elemental composition of basalt in the study area is quite complicated. However, the basalt chemical compositions show temporal (old to young) and spatial (north to south, west to east) variations in the major oxides, such as SiO2, TiO2, Al2O3, FeOt, MgO, CaO, Na2O, K2O, and P2O5. The difference in the relationship between the Mg# index (=Mg2+/(Mg2+ + Fe2+)) and the oxides between the basaltic regions is as follows:

– Period 15.5 - 8.5 Ma in Phu Yen (Song Cau - Ghenh Da Dia, Van Hoa, Cung Son): Compared with the whole study area, basalt in the early stage is low in MgO, CaO, and high in TiO2, Al2O3, FeOt, Na2O, K2O, and P2O5, and the SiO2 composition varies from low to high. Most major oxides form a linear correlation with Mg#. For example, Mg# correlates positively with TiO2 and negatively with Na2O, K2O, and P2O5 but exhibits a robust correlation with SiO2, Al2O3, and CaO.

– Period 7.5 - 4.5 Ma in Quang Ngai (Binh Chau, Binh Son, Ba Lang An, Sa Ky): basalt in this period is high in SiO2 and low in TiO2, Na2O, K2O, and P2O5. Mg# correlates negatively with SiO2 and positively with Al2O3, CaO, and TiO2.

– The period 3 to 0 Ma basalt in Quang Ngai, Dong Nai, Binh Thuan, and Ba Ria - Vung Tau (Ly Son Island, Bo Bai, Soc Lu - Thong Nhat, Hang Gon, Dat Do, Phu Quy Island, Hon Tro, Ba Ria - Vung Tau and continental shelf) has quite complex geochemical characteristics. According to the geographical location from north to south, in Quang Ngai province (Ly Son Island), the content of oxides SiO2, TiO2, FeOt, and P2O5 is low, and MgO, CaO, and K2O are high. In Binh Thuan province, Phu Quy Island area, the major oxides plot into high and low fields corresponding to the tholeiite series and sub-alkaline or alkaline basalt. The basalt of the early episode (2.4 Ma) has high SiO2 and Al2O3 composition, and the later basalt has high TiO2, K2O, and P2O5 content. The area of the Tro submarine has a major oxide composition quite similar to basalt in the upper part of Phu Quy Island. In Dong Nai province, Soc Lu area, the content of SiO2, Al2O3, FeOt, Na2O, and K2O is high and low TiO2, FeOt, MgO, and CaO.

Basalts in the East Vietnam Sea have low SiO2, MgO, and FeOt oxides content, similar to basalts in coastal areas and the South-Central continental shelf, but TiO2, Na2O, K2O, and P2O5 oxides are lower in the latter.

The trace element composition of basalt in the study area is normalized to the primitive mantle. Rare earth elements are compared to the chondrite, showing a decreasing trend line from strongly incompatible elements (Cs, Ba, Rb, Th) to highly compatible elements, such as Zr, Hf, Yb, Lu, reflecting typical oceanic island basalt features (OIB), often considered a product of the asthenosphere, formed from a relatively primitive mantle source. It is noteworthy that when compared with the primordial mantle, all basalt regions do not show negative anomalies (e.g., Nb, Zr, Ti), which may confirm that they are not contaminated with the crustal matter, including material brought down by subducted plates to the mantle.

1.3. Geochemical characteristics of primitive magma

1.3.1. Magma source characteristics of the study area

The magma source characteristics can be determined based on the relationship between pairs of trace element ratios such as Th/Yb – Ta/Yb and Nb/Y – Zr/Y (Pearce and Norry, 1979; Fitton et al., 1997; Pearce, 1982). Accordingly, the variation range of the ratio pairs is in the range Th/Yb = 1.0897 – 5.1393; Ta/Yb = 0.5518 – 2.3268; Nb/Y = 0.8617 – 3.8524; Zr/Y = 2.8486 – 16,6402. On the other hand, the relationship between the ratio pair Th/Y - Ta/Yb and Nb/Y - Zr/Y forms a positive correlation stretching along the intraplate basaltic melting field (OIB) and is not affected by crustal contamination or assimilation.

1.3.2. Primordial magma source

The fractional crystallization of olivine controls the magma differentiation characteristics occurring in the magmatic melt. The fractionation of olivine is considered a necessary condition to determine the chemical composition of primitive magma based on the principle of olivine compensation. According to the calculating results, the Mg# index of the primitive melts ranges from 58.79 to 68.09, and the SiO2 content ranges from 51.05 wt% to 43.19 wt%. The MgO value is high, ranging from 10.5 wt% to 15.33 wt%. The difference in the elemental contents in the primitive magma source reflects the changes in temperature and pressure states in the mantle over time and space.

1.3.3. Primitive magma temperature - pressure

According to various models, the melting temperature and pressure (Tf, Pf) can be determined based on the olivine thermometer. In order to increase the confidence of the computed results, it is common to apply multiple models simultaneously. Each model defines a value of melting temperature and pressure (Ti, Pi). The temperature and pressure of the magmatic melt (Tf, Pf) are determined as the models' average values of the temperature and pressure (Ti, Pi). The partial melting pressure and temperature parameters of the primitive magmatic melt in time are as follows:

– Period 15.5 - 8.5 Ma in Phu Yen (Song Cau - Ghenh Da Dia, Van Hoa, Cung Son): The melting temperature and pressure of primitive melt calculated according to the chemical composition of an alkaline basalt at Song Cau are very high, respectively, Tf = 14540C – 14700C and Pf = 25kbar – 27kbar.

– Period 7.5 - 4.5 Ma in Quang Ngai (Binh Chau, Binh Son, Ba Lang An, Sa Ky): The melting temperature and pressure of the primitive magma fluctuated, respectively, at Tf = 14350C – 14400C and Pf = 17kbar – 17.8kbar.

– The period 3 to 0 Ma in Quang Ngai, Dong Nai, Binh Thuan, and Ba Ria - Vung Tau (Ly Son Island, Bo Bai, Soc Lu - Thong Nhat, Hang Gon, Dat Do, Phu Quy Island, Hon Tro, Ba Ria - Vung Tau, and the continental shelf: The melting temperature and pressure of primitive melt at Ly Son Island (including Bo Bai) were Tf = 14570C and Pf = 24.3 kbar, respectively. At Phu Quy Island, the primitive melt occurred at melting temperature and pressure, respectively, Tf = 14410C - 14600C and Pf = 18kbar - 24 kbar, forming two distinct pressure groups. The basalt formed in the early stage at about 2.64 Ma under the melting pressure range of Pf = 18.3kbar - 19kbar, and the later stage had a higher melting pressure from Pf = 20.6kbar to 23.5kbar. In the area of Tro seamounts and the continental margin adjacent to the southwestern sub-basin of the deep basin, the melting temperature and pressure were, respectively, at Tf = 14300C - 14720C and Pf = 15kbar - 29kbar.

– The partial melting temperature and pressure of the primitive magmatic melts in the coastal area and the continental shelf show that the partial melting temperature in all three eruption periods is relatively uniform (about 14030C - 14800C). However, the partial melting pressure varies with time. The partial melting pressure was very high in the early period (15.5 - 8.5 Ma). The pressure is lower in the following period (7.5 - 4.5 Ma), at 17kbar - 17.8kbar. In the period of 3 to 0 Ma, the partial melting pressure of the primitive melt changes complexly. According to the computed data, some samples have low pressure (Tro seamount cluster), and the remaining samples generally have a pressure ranging from 18kbar - 29kbar.

– In the deep depressions of the East Sea, the partial melting temperature and pressure of the primordial molten and source were determined according to the results of chemical composition analysis of basalt samples obtained at IODP U1431, U1433, and IODP boreholes. U1434. Accordingly, the melting temperature and pressure of Tf = 14270C - 14680C and Pf = 17.5kbar - 28kbar, respectively.

1.3.4. Thermal state of the mantle (Tp)

– The mantle heat state was calculated according to the method of Putirka et al. (2007). According to the calculation results, in the coastal area and continental shelf, the mantle temperature (mantle thermal state) fluctuates in the range Tp = 14300C - 14930C, corresponding to the partial melting degrees of F = 3% - 8%. At the borehole location U1431, the mantle temperature fluctuates in the range Tp = 14130C - 14910C, corresponding to the degree of partial melting at F = 3% - 8%. At the borehole locations U1433 and U1434, the mantle temperature and partial melting degree are lower than in other areas, fluctuating from Tp = 14140C to 14610C, corresponding to the degree of partial melting from F = 3% to 5%. This result shows that the mantle thermal state of the study area is higher than the global average at 12800C.

2. Features of the geological structure of the study area

The oceanic crust of the EVS itself is divided into three different sub-basins: North, East, and Southwest. The structures in the South-Central and adjacent waters lie on the passive margin of the East Vietnam Sea, where the crust has been significantly thinned, with thickness ranging from 16 km to 24 km. The average depth of the Moho surface is about 20 km. The prime structural units of the South-Central Coast and adjacent sea areas (grade II structure) include (1) North Hoang Sa-Southern Hainan trough region; (2) Paracel-Macclesfield uplift blocks; (3) Phu Khanh transitional crust region; (4) Red River Basin; (5) Tri Ton uplift zone; (6) Tuy Hoa shear zone; (7) Phan Rang terrace. Further south and southwest is the Cuu Long basin, the Con Son uplift, the NE differential zone of the Nam Con Son basin, and the Dinh Trung basin, which is a deep depression extending from the deep-sea basin of the East Vietnam Sea to the southwest.

2.1. Features of regional Cenozoic stress field in the study area

The stress state in the South-Central Coast region is determined according to the analysis of cracks, slide surfaces, and scratches, especially in fault zones. Measurements were made on rocks of the Mesozoic to Cenozoic age, including basalts of the late Cenozoic age (from 9.6 to 9.1 Ma). The stress field is calculated according to the Delvaux and Sperner method. Results of determining the stress field, characterized by three principal normal stresses: $\sigma 1$, $\sigma 2$, $\sigma 3$ (where $1 > \sigma 2 > \sigma 3$) at ten survey locations are divided into four main groups including:

State of stress in the NW-SE direction: The stress state with maximum compression in the NW-SE direction, with the NE-SW oriented extensions acting as the dominant stress, mainly developing on the Mesozoic granite formations along the South-Central Coast.

Sub-latitude stress state: With north-south extensions, the sub-latitude compressive stress state mainly develops on Mesozoic-age granite formations along the South-Central Coast. Ratio $R = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3) = 0.08$ means $\sigma 2 \sim \sigma 3 << \sigma 1$, and index R' = 1.5 indicate faults formed in a stressed state with the characteristic normal strike-slip.

State of stress in the NE-SW direction: Compressive stress in the NE-SW direction is also recorded on the granite formations along the coast. Ratio R index R' = 1.5 - 1.97 shows that the faults formed in the stress state with characteristics of compressive strike-slip.

Sub-meridian compressive state: The sub-meridian compressive stress state is quite common in the study area. The results of stress state analysis show that the maximum compressive stress axis $\sigma 1$ is in the NE direction, the intermediate stress axis $\sigma 2$ is in the WNW direction, and the minimum compressive stress axis $\sigma 3$ is in the SE direction. The R ratio fluctuates in the range of 0.5 - 0.67, corresponding to the R' index ranging from 1.92 to 1.97, showing that the faults formed in the stress state with the characteristics of compressive strike-slip.

2.2. Linking primary tectonic phases in the study area

- ***Late Mesozoic tectonic phase***

The stress field characteristics analysis shows that the late Mesozoic tectonic phase in the South-Central area has the maximum compression direction oriented in the sub-meridian direction (from 330^0 to 355^0). The concentration of late magmatic lenses and dikes, mainly in the sub-meridian direction (as in Nha Trang), is evidence of the tectonic phase with sub-meridian compression. In addition, some brittle deformations through the sliding surfaces and scratches are evident on the schist surfaces in the La Nga Formation (such as in West Nha Trang), which are also tectonic activities occurring in the Late Mesozoic, with intensive NW-SE compression.

- ***The tectonic phases occurred in the Cenozoic***

Tectonic phase with sub-latitude compression: Analysis of the tectonic texture associations shows this phase also is widespread and intensive. Considering the age of the bottom-lined sediments discovered in the boreholes, this phase occurred around 36 Ma, i.e., starting from the end of the Eocene. The expression of the sub-latitude compression phase is observed in many places along the coastal strip of South-Central Vietnam, from Da Nang to Ninh Thuan, through pairs of coaxial faults NW-SE and NE-SW in the regions in granite block with sub-latitude compression, in which the NW-SE faults have the left-lateral slip mode, while the NE-SW faults have the right-lateral slip type. In addition, the sub-meridian-direction thrust fault system is also common, with a gently sloped sliding surface accompanied by sub-meridian-direction fractures.

Tectonic phase with sub-meridian and NE-SW compression: The most prominent feature of these phase tectonic activities is that the spreading and forward sliding activities occur mainly along the faults in the sub-meridian and NE-SW directions. This tectonic phase appeared strongly everywhere from North to South in the Late Miocene-early Pliocene (5.3-5.5 Ma), forming large regional unconformable surfaces and prolonging sedimentary interruptions in continental shelf basins. This tectonic phase also lasted until the modern period with an intermittent uplift of the South-Central and Western Highlands regions and subsidence at the seaside.

Modern tectonic phase: Earthquake data and global GPS show that at present, in Indochina and surrounding areas, there is a stress field with NWN compression direction.

CHAPTER IV. MANTLE DYNAMICS AND TECTONIC EVOLUTION IN THE CENOZOIC

1. Mantle dynamics model and tectonic evolution

1.1. Relationship between temperature, primordial magma volume pressure, and lithosphere extension coefficient.

The primary purpose of examining the relationship between melting depth and lithosphere extension is to provide a semi-quantitative assessment of the potential for melting in the mantle when the lithosphere is stretched. Experimental results of several studies show that when stretched due to tectonic activity, the thickness of the lithosphere plays an essential and decisive role if melting occurs in the mantle. However, for the melting process to occur in the mantle, it must satisfy that the mantle thermal state (Tp) is higher than the average (12800C) and reaches about 14800C. Then the melt masses generated in the mantle will depend on the parameters of Tf, Pf, H, βm, βc; where Tf, Pf are the partial melting temperature and pressure of the primitive magma, H is the melting depth, and βm, βc is the extension coefficients of the lithosphere and the crust).

Applying the research results of Latin and White (1990) to calculate, the lithosphere extension coefficient in the study area fluctuates in the range βm = 2.04 - 2.13. The appearance of step-downward normal faults on the continent of the study area shows that it is influenced by uniform extending activities. This result means that in the average mantle temperature Tp = 12800C, the mantle in the study area does not generate melting. However, when the mantle thermal state is high (Tp = 14800C) in the mantle, melting can occur. In the deep-basin areas of the East Vietnam Sea, the lithosphere extension coefficient varies in the range βm = 2.04 - 2.13; this coefficient is relatively small; therefore, only a small amount of melting mass is generated.

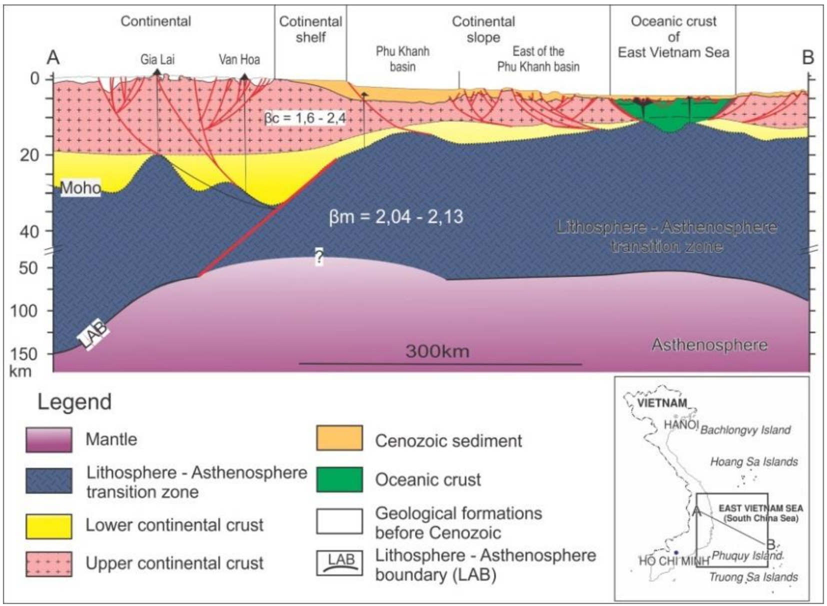

Figure 6: *Synthetic cross-section of the deep structure of the continental shelf area built according to the seismic data of the project KC09.07/16-20; the mainland is built based on the geological-mineralogical map of scale 1:200,000, and the Moho surface was built based on the results of N.N. Trung and N.T.T Huong (2010). LAB depth (Boundary between lithosphere and asthenosphere) is according to Chen et al. (2021). The lithosphere extension coefficient βm is calculated according to expression (1) of Latin and White (1990).*

1.2. Current mantle cross section in the study area

Melting source peridotite (ultramafic rock) forms basalt fusion. The chemical composition of the solution is characterized by low SiO_2 content (less than 52%), relatively high MgO (5% –15%), and total alkalinity of less than 5%. In some previously published works, the authors divided the upper part of the mantle into mineral zones corresponding to mineral facies zones (in order of increasing depth), including 1) Zone I: plagioclase peridotite; 2) Zone II: spinel peridotite; 3) garnet peridotite. The boundaries of mineral facies are established based on phase transformations. The boundary between zones I and II is based on the equilibrium of spinel (Sp) + enstatite (En) = olivine (Ol) + pyrope (Pyr), between zones II and III: graphite (C) = diamond (D). Besides, McKenzie and Bickle (1988) and Latin and White (1990) suggested that the increase in temperature of the mantle to about Tp > 1400^0C, in the case of lithosphere extension at special conditions, will cause melting. In studying late Cenozoic magmatic sources in the South-Central and Western Highlands, Hoang and Flower (1998) determined that the structural characteristics of peridotite zones in the study area occurred at shallower depths than those of experimental results.

From the results obtained in the thesis and linked with the geophysical data in the literature, the researcher has built a cross-section model of the mantle structure that cuts through the Binh Chau and Ly Son areas, reflecting the characteristics of the mantle structure of the study area at present (Figure 7). Accordingly, the mantle thermal state is higher than the average (estimated Tp = 1480^0C), and the mantle source's partial melting pressure and temperature are Tf = 1458^0C, Pf = 24.3 kbar, and the partial melting degrees of about F = 3-5%. At the continental shelf, a mantle flow zone due to forced upwelling is determined, causing the disappearance of the LAB boundary corresponding to the garnet lherzolite field at a depth of about 65km - 150km.

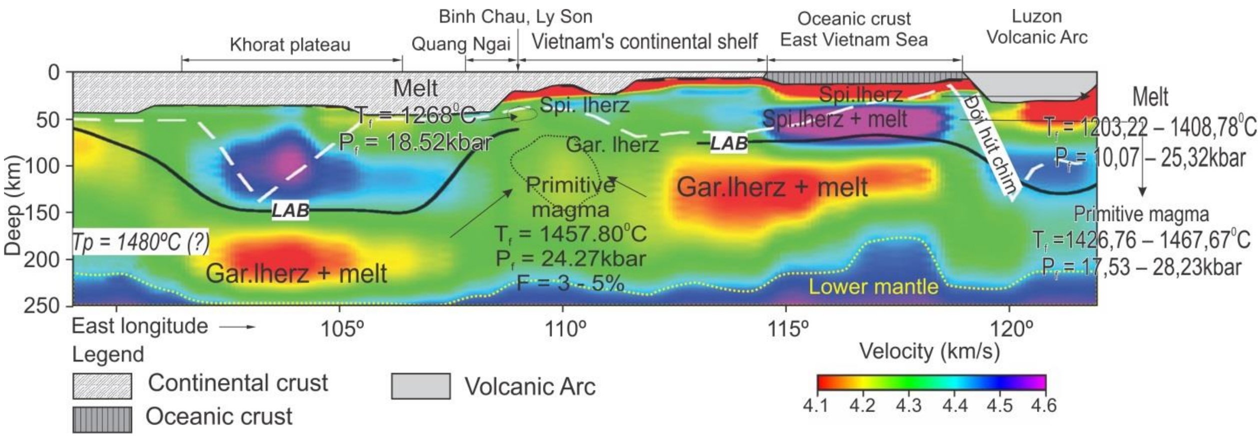

Figure 7. *Seismic cross-section model (current time) illustrating the characteristics of the upper mantle structure through Binh Chau, Ly Son, and the continental shelf of Quang Ngai province (after Chen et al., 2021); mineral phase transition zone is after P.T. Xuan and N.X Khan (1996) and Hoang and Flower (1998.)*

2. Evolutionary model of mantle-lithosphere geodynamics in the South-Central Coast and surrounding areas

The history of geological development in the Cenozoic period in Southeast Asia and the study area, in particular, is strongly influenced by two major tectonic activities. The Indo-Eurasian plate collided in the Early Eocene - Middle-Late Miocene and the tectonic activity of the East Vietnam Sea formation took place around the Early Oligocene to the Early - Middle Miocene.

The research results on the tectonic structure and mantle dynamics allow the researcher to build a complete context of the mantle-lithosphere evolution stages in the study area into six main stages, including:

- Stage 1: Before the Middle Eocene (~ 45 Ma) - The pre-rifting period.
- Stage 2: Middle Eocene – Early Oligocene (~ 45 – 33 Ma) - The rifting period.
- Stage 3: Middle Oligocene - Late Oligocene (33 - 23 Ma) - The bottom extension phase formed the East Vietnam Sea's oceanic crust in the east.

– Stage 4: Early - Middle Miocene (about 23 Ma - 16 ±0.5 Ma) - The period of expansion of oceanic crust into the continental shelf of Vietnam.

– Stage 5: Middle Miocene - Pliocene (from 16±0.5 to 5 Ma): The post-extension phase with volcanic eruptions formed the basal layer.

– Stage 6: Pliocene – Quaternary (5 to 0 Ma): The post-extension phase with a single volcanic eruption.

2.1. Before the Middle Eocene (before 45 Ma) - The pre-rifting period

In the Paleogene - Middle Eocene period (before 45 million years), the study area was part of the Indochina block associated with South China - North Vietnam block, forming the Southeast edge of the Eurasian lithosphere plate. Before the Indo-Eurasian collision, the location of the study area was quite far to the northwest compared to today's position. On the continental shelf of Vietnam, the Hoang Sa archipelago, Macclesfield shoal, Reed Bank, Truong Sa archipelago, and Palawan Island were adjacent. In general, in the Paleogene - Middle Eocene period, the study area had relatively stable tectonic activity. The upper mantle did not fluctuate; the mantle thermal state was estimated to have an average value of about Tp = 1280^0C, and the thickness of the lithosphere was estimated according to the global average value of about 100km.

2.2. Middle Eocene – Early Oligocene (~45 - 32 Ma) – Rifting period

At the time of the Middle Eocene (~45 Ma ago), the Indian plate began a hard collision with the Eurasian plate. The consequence of the collision is the displacement of the Indochina block to the Southeast in the direction of left-lateral motion along the Red River fault, accompanied by a clockwise rotation, triggering rifting phase of the area that only ended when the extension of the bottom bed of the East Vietnam Sea began. At this stage, the dynamic mode was expressed by brittle faults that developed intensively in the upper part of the crust. According to the analysis results of the thesis, the regional stress state in this period was sub-latitude compression and sub-meridian extension on the Indochina tectonic leveled surfaces formed in the previous period. On the continental shelf of the study area, scattered rift structures had been developed, creating momentum for the development of Cenozoic tectonic structures, especially the Tertiary sedimentary basins, as well as a series of trenches and troughs scattered in the area, with the dominant direction being sub-latitude (Figure 8).

In the west of the study area, two mantle currents appeared, corresponding to a depth of about 150-200km (shallow mantle flow) moving north, northwest-southeast, and a mantle flow with a depth of over 200km (deep mantle flow) moves southwest-northeast from the Indian Ocean. The appearance of the shallow mantle flow is explained by the collisional displacement of the Indian plate into the Eurasian plate, leading to the asthenosphere flow moving from the Indian Ocean to the north. When part of the Indian plate was subducted, part of the crust was deeply embedded in the mantle, hindering the movement in the northeast direction; over time, the gyro-sphere was forced to bulge in the east-west direction and reverse in the northwest-southeast direction and penetrate the mantle in the study area. The deep mantle is believed to be the dispersive gyro-sphere from the Indian Ocean, partly moving northeastward into mainland Southeast Asia. The interaction between the deep and shallow mantle flows at a depth of 200km may have formed an upwelling zone and increased the mantle thermal state from the average (1280^0C) to 1480^0C (according to the thermal calculation results from the primitive magma source).

The influence of mantle dynamics on the tectonic evolution of this period is not clearly shown on the Earth's surface; however, according to the geochemical data of the primitive magma source, it is possible to conclude that the thermal state of the mantle in the study area began increased from 1280^0C to about 1480^0C. Although the role of mantle dynamics in the formation of the East Vietnam Sea is still a matter of further research, two deep mantle flows can be seen moving to the south of Hainan Island and the Phu Khanh basin area, and the east is the locations where the East Vietnam Sea spreading axes are formed (Figure 8). The elevation of the mantle's thermal state makes the melting process easier. Then, in the upper mantle, it is easy to form magma sources in the upper mantle layer (100 - 200km). One of the mantle flows observed in the upper mantle west of the study area (zone 5) was formed, corresponding to the distribution field of garnet peridotite (Figure 8).

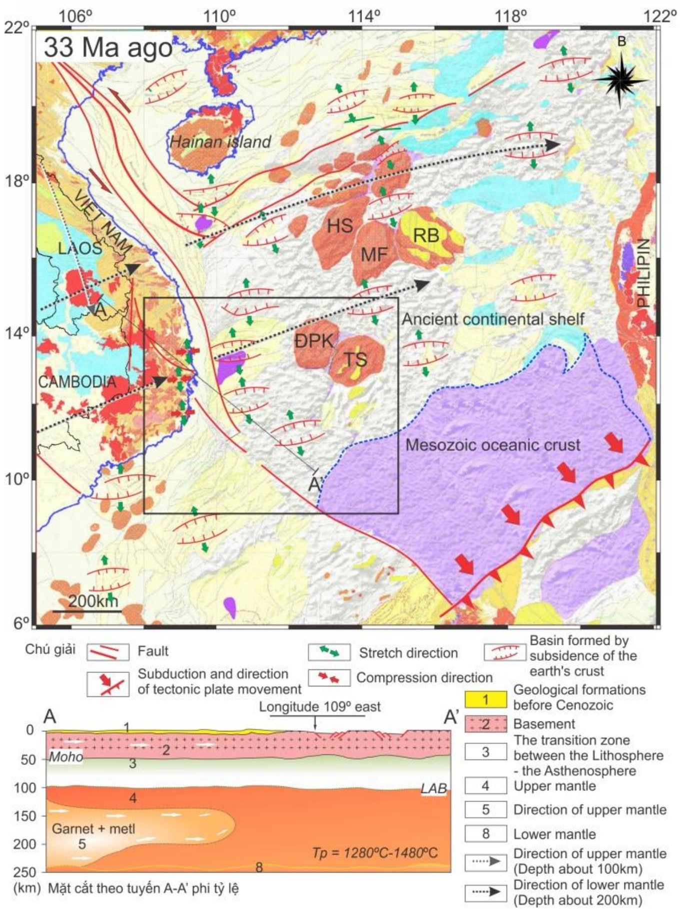

Figure 8: *Tectonics - geodynamics context of the East Vietnam Sea period 33 Ma*

2.3. Middle Oligocene - Late Oligocene (33 - 23 million years ago) - The bottom extension period forming the oceanic crust of the Eastern East Vietnam Sea

In the EVS, about 33 million years ago (some believed to be 32 Ma), the extending and rifting activities reached the point of starting the process of exposing the oceanic crust in the northern area of the marginal sea (Fig. 9). The bottom stretching causes the oceanic crust to expand to the North-South. After that, the bottom spreading axis tends to move to the South. About 25 million years ago, the phenomenon of "jumping the bottom spreading axis" happened for the second time to the South, and at the same time, the NNW - SSE Reed Bank fault appeared, controlling the West of the EVS's seabed expansion, accompanied by the appearance of a new bottom spreading center to the southwest of this fault. Thus, two parallel extension centers develop independently (Figure 10). The southwest bottom spreading center is smaller and has the NE-SW direction, i.e., the extension direction is NW-SE and has a narrower shape towards the SW. Thermal subsidence took place in the Early Miocene (about 23 million years ago) on the continental shelf of South-Central Vietnam (Phu Khanh basin area). Manifested by an increase in the thickness of early Miocene sediments accompanied by a rise of the molten zone in the mantle can be observed in seismic profiles cutting through the South-Central continental shelf.

During this period, the main rifting of the area ended. According to the analysis results of the thesis, the regional stress state in this period was sub-latitude compression and sub-longitude extension. It tended to shift northeast-southwest around 24 million years ago, gradually perpendicular to the northeast expansion of the Phu Khanh basin (Figure 10). The formation of the oceanic crust in the East Vietnam Sea reflects the prominent role of mantle dynamics in tectonic evolution. As argued in the thesis's research, lithosphere expansion in the EVS and the adjacent continental shelf is a magma-poor process, which means that the extension of the lithosphere is not large enough to cause melting to form magma or the amount of melt volume generated is not significant to form the basalt crust of the EVS. However, the reality shows that the oceanic crust of the EVS is pure basalt crust. Thus, to form a large enough amount of creating a volcanic crust, there must be an interaction of mantle dynamics large enough to produce voluminous lava flows forming a lava-made crust. In the study of Le Duc Anh et al. (2017), a thesis result, the authors determined that the thermal state of the mantle in the Northern East Vietnam Sea during this period fluctuated around Tp = 1380^{0}C - 1500^{0}C (sample ZK05, 20.1 Ma), the melting depth is about 60km, corresponding to the spinel lherzolite source. Figure 9 illustrates the shifting trend of the deep mantle flow passing through the oceanic crust of the EVS in the early period, although there are various views on the formation of the oceanic crust in the marginal sea during this period. However, in the high mantle thermal state, the primitive magma source depth is relatively shallow (60km), significantly lower than the original LAB depth surface (about 100km), demonstrating mantle dynamics' impact on regional tectonics in the East Vietnam Sea. The rapid decrease in LAB surface depth has changed the matter density in the mantle-crust transition zone to form small-scale convection swells and longitudinal shear stresses. The rising factors have promoted the stretching and forming of the oceanic crust of the East Sea in the early stage.

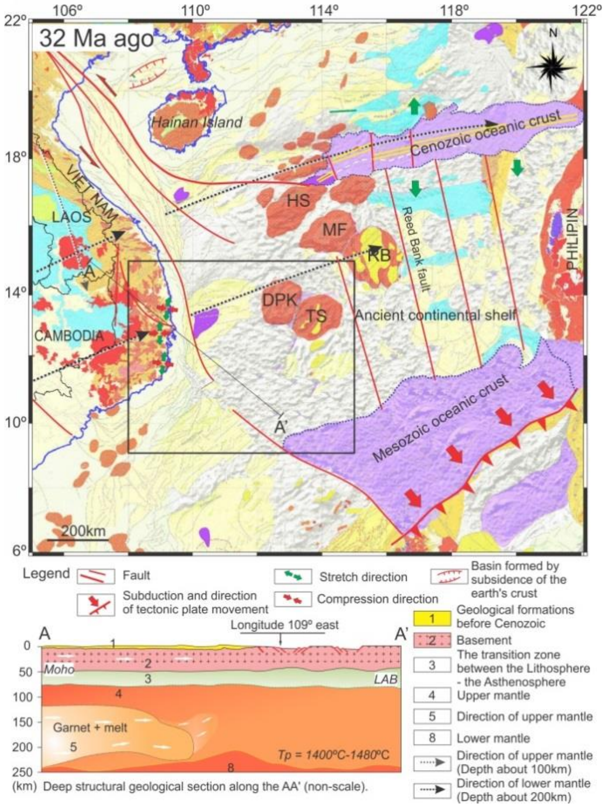

Figure 9. *Tectonics - geodynamics context of the East Vietnam Sea period 32 Ma: the beginning of the bottom expansion to form new oceanic crust*.

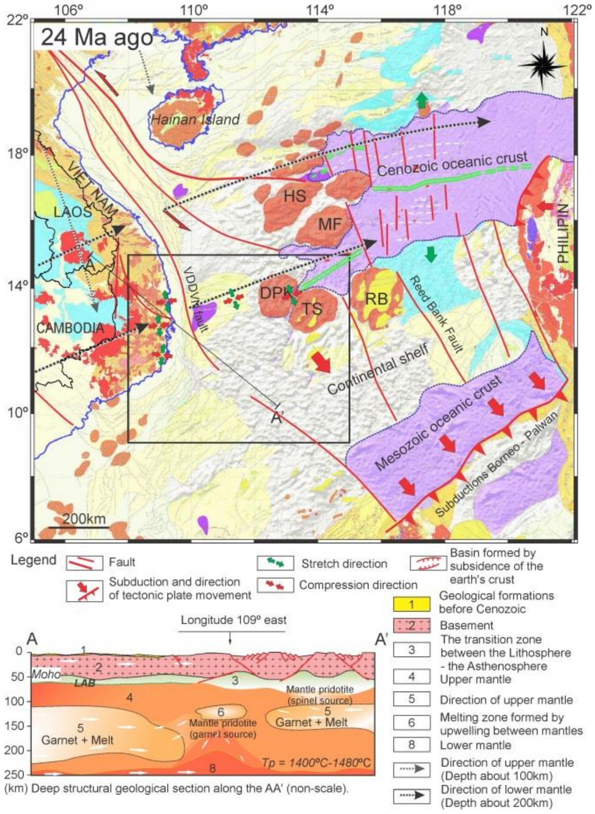

Figure 10. *Tectonics - geodynamics scenario of the East Vietnam Sea in the period 24 Ma (Late Oligocene).*

In the study area, the role of mantle dynamics was expressed in the Late Oligocene - Early Miocene period when the East Vietnam Sea spread to the southwest and the extension of the Phu Khanh basin due to thermal subsidence. According to the experimental petrologic model, the wave propagation anomaly zone corresponds to the garnet peridotite distribution field (anomalous zone No. 6, Figure 10). The depth of the distribution field fluctuates in the range of 110km - 120km, much shallower than the two high-temperature wave propagation anomalies No.5 corresponding to the distribution field of garnet peridotite + melt (anomalous zone No. 5, Figure 10). As argued, lithosphere extension during the rifting phase does not form a magma mass, so the garnet peridotite distribution field (anomalous zone 6) can be formed by being partially separated from the two fields of garnet peridotite garnet + melt (anomalous zone 5) and/or due to the rise of deep mantle currents (depth > 200km, anomalous zone 10) (Figure 10). Under the rising impact of the mantle at this stage, the thickness of the lithosphere in the study area began to be thinned, and the crust was stretched, causing the extension of sedimentary basins.

2.4. Early Miocene - Middle Miocene (about 23 Ma - 16 ±0.5 Ma) - The period of oceanic crust expansion into the continental shelf of Vietnam.

In the Early-Middle Miocene, the opening of the EVS spread to the SW, deep into the continental shelf of Vietnam (Figure 10). The bottom extension ended about 16 ±0.5 million years ago. Sedimentary basins on the continental margin of Vietnam gradually shifted from the sub-latitude to the NE - SW direction, with a clear NW - SE extension (Figure 11). At the same time, this period began with the participation of trans-crustal faults, which controlled the extension of the sedimentary basins. According to the analysis results of the thesis, the regional stress state in this period is compression in the NE - SW direction, and the extension in the northwest-southeast direction coincided with the extension direction of the Phu Khanh basin and the propagation direction of the spreading axis of the EVS in the late stage (Figure 11).

The role of mantle dynamics in tectonic evolution is shown in basalt's geophysical and geochemical data. Oil and gas seismic data from the literature shows that the occurrence of trans-crustal faults controls the extension of the sedimentary basins, and at the same time, in the center of the basin, the crust is thinned and stretched. In the deep depressions of the EVS, the crust is stretched and thinned, revealing the oceanic crust towards the continental shelf of Vietnam (Figure 11). As discussed, the lithosphere in the EVS is not extended enough to generate enough magma mass to form an oceanic crust, so mantle flows must provide a significant heat source for melting. According to the results of the thesis, the depth of primitive magma source in the continental shelf of Vietnam ranges from 45 - 80km, and the composition of trace elements and rare earth elements shown on the spider charts shows a decreasing trend from highly incompatible elements to the group of more compatible elements characterizing the typical characteristics of oceanic island basalts. They are most likely derived from garnet or transitional spinel-garnet peridotite sources.

On the one hand, they form a source of spinel peridotite magma which is a source of forming oceanic crust in the EVS; on the other hand, a source of garnet peridotite-induced magma (smaller scale) causes subsidence, thinning, and stretching crust in the South-Central continental shelf of Vietnam (Figure 11). Thus, the primitive magma source in the continental shelf of Vietnam can all be derived from a source of about 120-200 km, corresponding to the garnet peridotite + melt field. However, the influence of the dynamic regime when the mantle flow moving (reflected through changes in pressure, formation depth, and thermal state) directly affected the tectonic context of the East Vietnam Sea in the period from 23 Ma - 16 ±0.5 Ma.

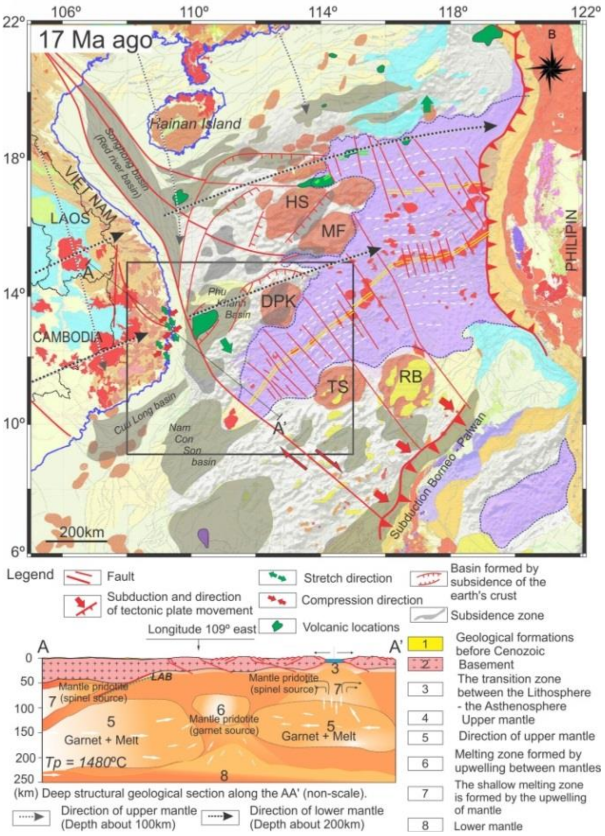

Figure 11. *Tectonics - geodynamics context of the East Vietnam Sea period 17 Ma (Early-Middle Miocene)*

2.5. Middle Miocene - Pliocene (from 16 ±0.5 Ma to 5 Ma): The post-spreading phase with volcanic eruptions forming the basal layer

During the Middle Miocene - Pliocene period (from 16 ±0.5 Ma to 5 Ma), the main tectonic activities in Southeast Asia ceased. At this time, the East Vietnam Sea stopped spreading, and the movement of plates and microplates along major faults also stopped. According to the thesis results, the study area was under NE - SW stress, gradually shifting to the north, northwest-south, and southeast. The recorded tectonic events are mainly local, such as tectonic inversion north of the Red River Basin and lateral strike-slip by NE - SW stretching in the Van Hoa plateau...

Although the manifestations of horizontal displacement of plates, microplates, and geological structures are only local and small-scale, uplifting, and subsiding processes accompanied by basalt eruption were common in sedimentary basins on the mainland Vietnam, the South-Central region, the Central Highlands, and some neighboring countries such as Laos, Cambodia, and Thailand.

According to the mantle flow model of Jolivet et al. (2018), in case the displacement velocity of the shallow mantle flow (at a depth of about 100km) was 5cm/year; at this time, and the mantle flow began to cover the entire upper mantle over Southeast Asia and the continental shelf of Vietnam (Figure 12). This phenomenon shows that mantle dynamics play a crucial role, dominating the tectonic evolution of the Middle Miocene - Pliocene period in Southeast Asia.

In the study area, the role of mantle dynamics is clearly shown through deep seismic and basalt geochemical data. As discussed in the above research, in the Eocene-Oligocene-Early Miocene, the sedimentary formations in the Phu Khanh basin were the formations of lakes, rivers, streams, and shallow seas. Late Miocene - early Middle Miocene, this area also strongly developed coral reef formations, demonstrating the shallow marine environment. However, from the middle Miocene (about 16-17 Ma), the Phu Khanh basin's sedimentary environment changed radically to the deep-sea environment. According to the sea level fluctuation suggested by Haq et al. (1988), the average world ocean level in the period 17-14 Ma was +140m, showing no significant increase, but on the contrary, it mainly decreased gradually. Thus, the relatively rapid change from the shallow marine environment to the deep-sea environment must be due to the tectonic process causing the subsidence of the crust.

According to the thesis results, the depth of magma sources in the coastal areas of Quang Ngai and Phu Yen varies from 40 to 80 km, corresponding to the spinel peridotite distribution field to the upper part of the garnet peridotite field. The study's rare earth elements of basalt normalized to chondrite patterns show a steep curve from light (La to Nd) to heavy rare earth elements (Ho to Lu). The trace element primitive mantle normalization also shows a steep trend from highly incompatible elements decreasing to elements with higher compatibility, the characteristics commonly observed for oceanic island basalt.

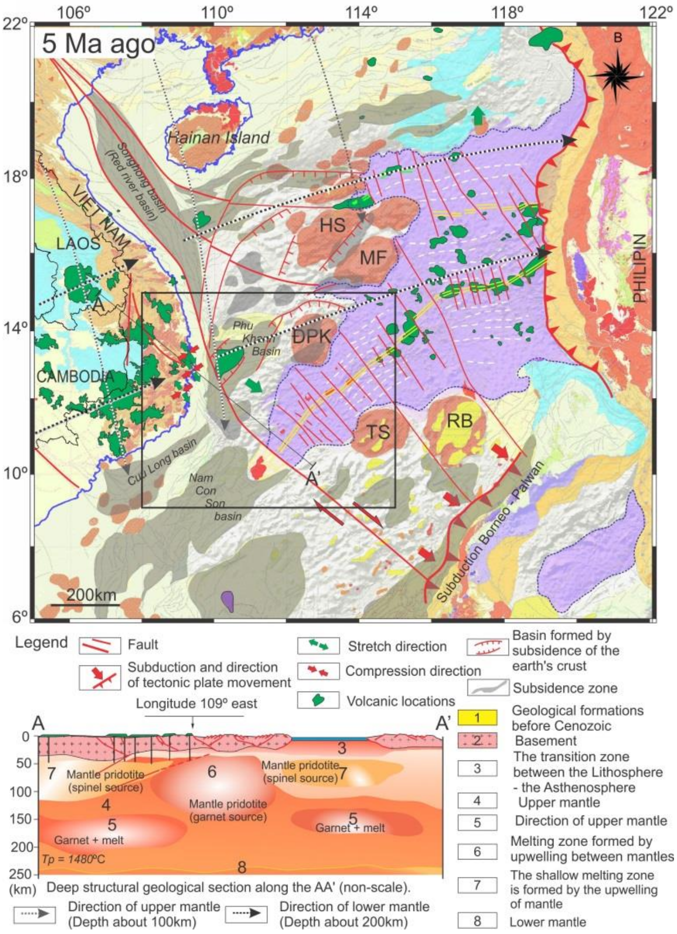

Figure 12. *Tectonics - geodynamics context of the East Vietnam Sea in the period of 5 Ma; volcanic eruptions in the early stages of the continental shelf and the South-Central Coast.*

Basalts of 15.5 - 8.5 Ma and 7.5 - 4.5 Ma periods show high and low heavy rare earth element contents, respectively. Notably, comparing the composition of heavy rare earth elements in basalts from the mainland and the East Vietnam Sea basin, there is a wide range variation in the coastal and continental shelf, from lower to higher than that of the EVS basin (spinel peridotite source), meaning that the primitive magma of basalt in the study area can be derived from garnet peridotite source which tends to retain heavy rare earth elements in residuals. The cross-section in Figure 13 shows the expansion of the garnet peridotite source (zone 6), marking a significant rise of the mantle, leading to a sudden change in the thickness of the lithosphere-asthenosphere transition zone (LAB). This sudden change has generated longitudinal shear stress, causing the crust to subside quickly, and triggering volcanic eruptions. Volcanic eruptions were widely spread in the Western Highlands, producing voluminous tholeiitic to sub-alkaline basalt with a depth of magma generation estimated at 40-50km, corresponding to the spinel peridotite distribution field. Consequently, a shallow mantle (about 100km depth) was forced to uplift and extrude from the Himalayas to the study area (Figure 12). The magmatic activity in this period in Southeast Asia and the continental shelf can be considered the energy release process of shallow mantle intruding and compressive uplift.

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2.6. Pliocene - Quaternary period (5 Ma - 0 Ma) – Post-rifting phase with monogenic volcanic eruptions

In the Pliocene - Quaternary period, tectonic activity in Southeast Asia was relatively stable because the main tectonic events of the region had previously stopped. The most significant difference between this phase and the previous one is the end of the tectonic uplift, subsidence, and basaltic eruptions forming the basal cover due to the displacement and extrusion of the shallow mantle flow (at a depth of about 100km) in the continental shelf of South-Central Coast, Western Highlands, and some Southeast Asian countries. According to petroleum seismic data, the late Miocene sedimentary layer is relatively stable, on which mainly young, discontinuous faults developed on the background of previous fault zones. According to the thesis results, the study area was influenced by the north, northwest-south, and southeast stresses (Figure 13).

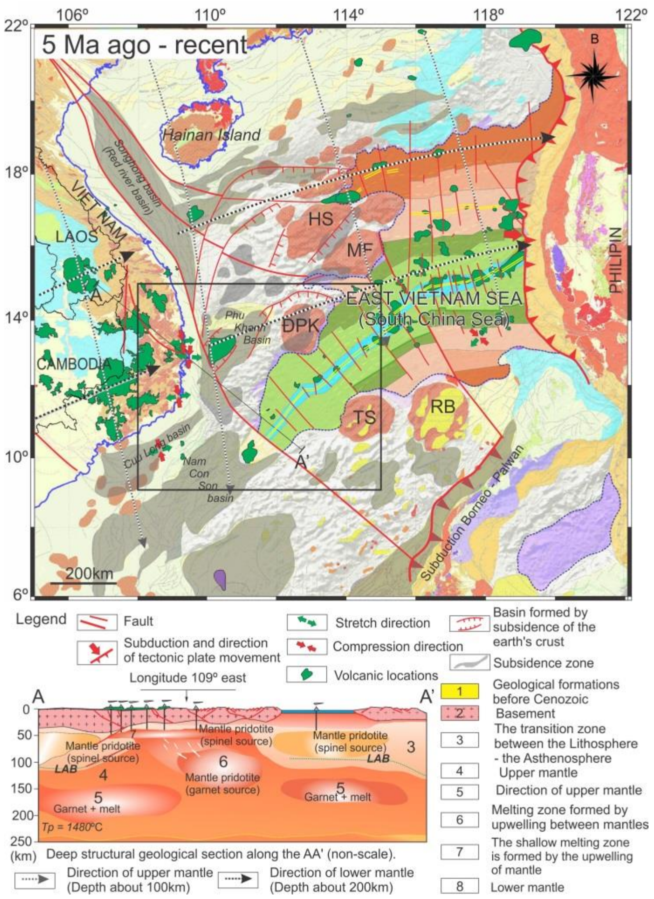

Figure 13. *Current situation of the East Vietnam Sea*

In the study area, the role of mantle dynamics in the tectonic evolution of this period is shown by monogenic basalt eruptions distributed along the EVS spreading axis, continental shelf, South-Central Coast and Western Highlands. According to the thesis results, the magma volume in this period is relatively small, mainly geochemically enriched alkaline and sub-alkaline basalts, relatively primitive, and of oceanic island type. Notably, numerous ultramafic mantle inclusions of different sizes in alkaline basalt are found at Phu Quy Island, Hon Tro seamounts, and elsewhere South-Central coastal region. The depth of the magma source ranges from 70-80km. Especially basalt in this period has low heavy rare earth element content compared to the EVS basin basalt and the basalt formed in previous stages. Although the magma source depths are relatively shallow, geochemical characteristics suggest they are derived from garnet peridotite sources (Figure 13).

The cross-section in Figure 13 shows the deep structural characteristics of the study area from 5 Ma to the present, showing that in the deep-lying area of the EVS, in the mantle-lithosphere transition zone, the process of decompression and cooling took place rapidly following the lowering of the LAB boundary surface to about 100km.

The rapid decrease in temperature and increase in thickness of the mantle-lithospheric transition zone has caused the upper mantle to produce enough magma to form a new oceanic crust; the process is considered one of the reasons leading to the East Sea stopped spreading. The monogenic volcanic eruption is mainly derived by melting the peridotite garnet source ignited by mantle extrusion from deep below, evidenced by the geochemical characteristics of basalt samples from the continental shelf and along the South-Central Coast. Besides, the cross-section in Figure 14 also shows the transition of extrusion and intrusion into the South-Central region. Thus, in this period, the mantle dynamic regime has the characteristics of releasing residual energy of the previous Middle Miocene - Pliocene tectonic period.

CONCLUSIONS

Cenozoic tectonic activity in the study area is intensively and decisively affected by the India-Eurasia plate collision. This process causes displacements along major regional faults and mantle flows, which promote spreading at the eastern edge of Eurasia, contributing to the formation of marginal seas in the Western Pacific Ocean and controlling the structural-tectonic plan of Indochina and the East Vietnam Sea today. According to the thesis results, the graduate student has the following conclusions:

(1) Mantle dynamic mode includes melting temperature and pressure, melting degrees, and upper mantle thermal state. At the time of melting, the upper mantle temperature in the study area was higher than 1400^0C, about 120^0C higher than the average global mantle temperature.

(2) The high mantle temperature in the region is the main driving force for melting in the upper mantle, while the lithosphere extensionβm in the region ranges from 2.04 to 2.13, not enough to cause decompression melting to form magma. This result shows that the elevation of the mantle thermal state is the primary mechanism for forming the East Vietnam Sea oceanic crust and Cenozoic basalt formations.

(3) The process of tectonic evolution in the South-Central region and adjacent areas is strongly influenced by tectonic stress fields, with the leading resource being the interaction between large lithospheric plates in the region. However, lithosphere deformation due to plate interaction is insufficient to generate the magmatic melt mass forming the oceanic crust of the East Vietnam Sea and triggering late Cenozoic volcanism on the continental shelf and coastal region in South-Central Vietnam

(4) The geological evidence obtained in this study shows that it is necessary to divide in more detail, specifically for the magmatic-tectonic stages after 16 million years. Accordingly, the study area experienced six periods of magmatic-tectonic activity, including 1) Before the Middle Eocene (> 45 million years): the pre-rifting period; 2) Middle Eocene – Early Oligocene (45 - 33 Ma): the rifting period; 3) Early Oligocene - Late Oligocene (33 - 23 Ma) and 4) Early - Middle Miocene (about 23 Ma - 16±0.5 Ma): the period of expansion of oceanic crust entering the shelf Vietnam mainland, 5) Middle Miocene - Pliocene (from 16±0.5 Ma to 5 Ma): The post-extension period with volcanism by fissure eruptions to form basal (basement) layers, 6) Pliocene - Quaternary period (5 Ma - 0 Ma) - The post-extension phase characterized by monogenic volcanic eruptions.

The work was completed at the Graduate University of Science and Technology, Vietnam Academy of Science and Technology.
Scientific supervisor 1: Dr. Phung Van Phach
Scientific instructor 2: Assoc. Prof. Dr. Nguyen Hoang

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