PETROVIETNAM JOURNAL
Volume 10/2020, p. 12 - 19
ISSN 2615-9902

PRELIMINARY ASSESSMENT OF THE CHARACTERISTICS OF LATE MIOCENE - QUATERNARY INTRUSIVE AND EXTRUSIVE MAGMATISM IN THE TU CHINH - VUNG MAY BASIN, SOUTHEASTERN CONTINENTAL SHELF OF VIETNAM

Bui Huy Hoang, Le Chi Mai, Ngo Thi Van Anh
Vietnam Petroleum Institute
Emai: hoangbh.epc@vpi.pvn.vn
https://doi.org/10.47800/PVJ.2020.10-02

Summary

Based on the seismic and well dataset provided by the Vietnam Petroleum Institute (VPI), the authors have mapped and described the characteristics of the distribution and morphology of magmatic bodies as well as relatively dated them in the Tu Chinh - Vung May basin and adjacent areas. To distinguish magmatic bodies from other amplitude anomalies such as gas zone or carbonate build-up/layers, multiple criteria were used such as cross-cutting relationship, associated deformation of surrounding strata, morphology and geological relationship between different magmatic bodies. Intrusive bodies are usually sheet-like or saucer-shaped sills that cross-cut strata and even deform overlying strata, while extrusive bodies are usually cone-shaped vents/volcanoes or extensive lava sheets that conform to strata. The magmatic bodies often distribute in clusters around one or more magmatic conduits. Middle Miocene and older syn-rift faults controlled the pathway of the conduits. Magmatic bodies are more abundant closer to the East Sea spreading margin. Late Miocene - Quaternary magmatism is widespread in the study area in particular, and in the East Sea and adjacent areas in general. These activities took place after rifting and oceanic crust formation had ended, which is characteristic of magma-poor margins.

Key words: Intrusive, extrusive, Tu Chinh - Vung May basin, Late Miocene - Quaternary, Vietnam continental shelf.

1. Introduction

Late Miocene - Quaternary magmatism is widespread over the East Sea and adjacent areas [1, 2], yet there are not many studies on the spatial and temporal distribution as well as the geological relationship between magmatic bodies in the Vietnam continental shelf. This paper presents the morphology, age, distribution pattern and geological relationship of the Late Miocene - Quaternary intrusives and extrusives in the Tu Chinh - Vung May basin, southeastern continental shelf of Vietnam (Figure 1), based on VPI's seismic and well dataset updated until 2020.

2. Geological settings

The study area covers the majority of the Tu Chinh - Vung May basin and the eastern part of the Nam Con Son basin (Figure 1). During the Eocene - Middle Miocene, the study area underwent two phases of continental rifting closely related to the seafloor spreading in the East Sea: 1) N-S extension during Eocene - Early Oligocene; and 2) NW-SE extension during the Early - Middle Miocene [4 - 6]. The rifting process led to extreme thinning of the continental crust around the seafloor spreading domain, with a continent-ocean transition zone of up to hundreds of km wide [7, 8].

From the Late Miocene to date, the tectonic regime is dominated by thermal subsidence. At the same time, basaltic magmatism occurred throughout the East Sea as well as in South Central Vietnam [9, 10]. Magmatism in hyper-extended crust around the East Sea oceanic domain has been documented in the Pearl River Mouth basin [11], Qiongdongnan basin and the Hoang Sa basin [12], and Phu Khanh basin [4]. Magmatism is also recognised in the oceanic domain during this time [13]. The widespread magmatism occurred after rifting and

Date of receipt: 19/10/2020. Date of review and editing: 19 - 30/10/2020.
Date of approval: 30/10/2020.

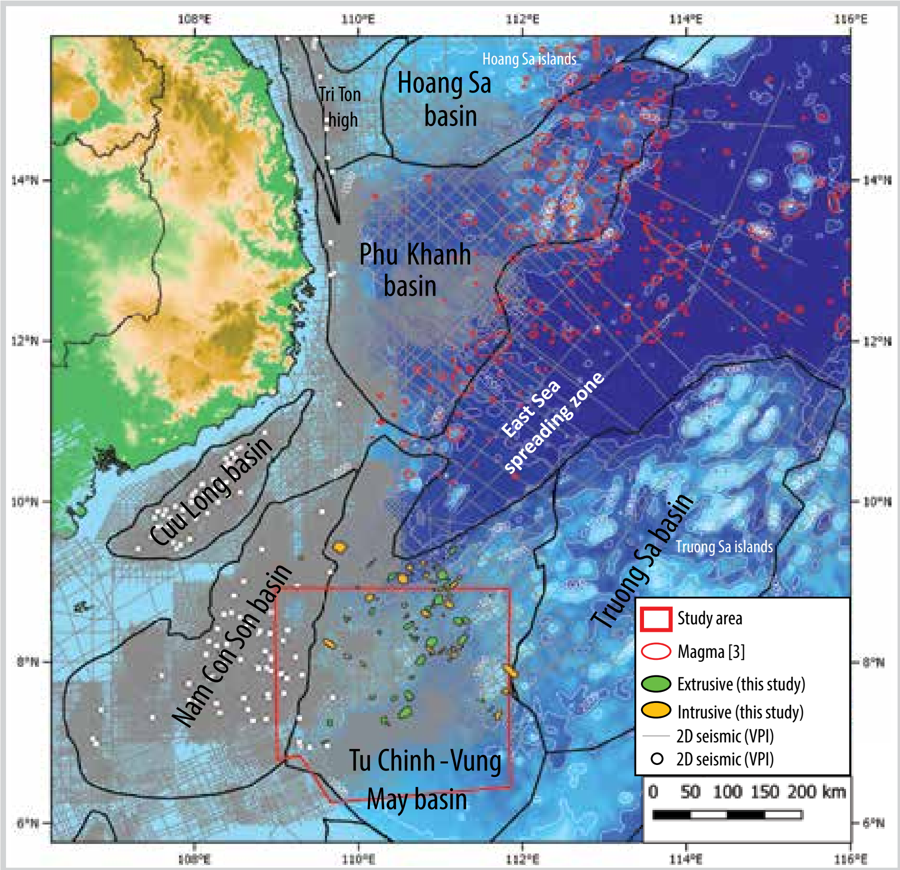


Figure 1. *Location of the study area and the seismic and well database used in the study. Post-rift magma distribution in the East Sea outside the study area [3].*

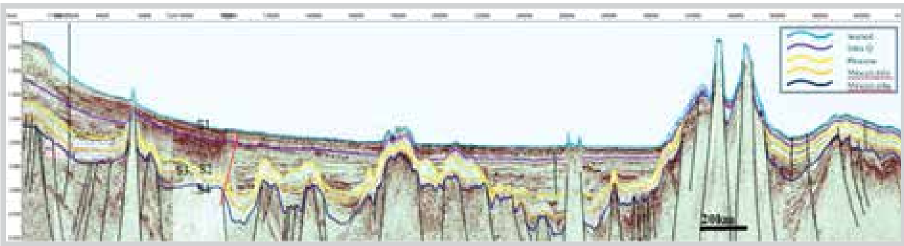


Figure 2. *Regional stratigraphic correlation using intergrated well and seismic data in the study area.*

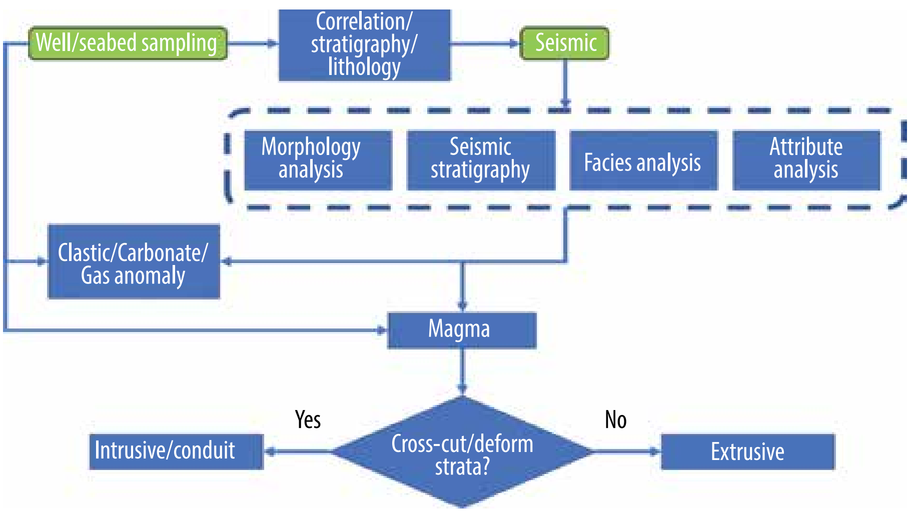


Figure 3. *The study's workflow for identifying magmatic bodies and distinguishing them from gas anomalies and carbonates.*

oceanic crust formation ended, which is characteristic of magma-poor margin [3, 7].

3. Database

To determine the spatial distribution of different phases of magmatism during the Late Miocene - Quaternary, we used an integrated dataset of seismic and wells from the petroleum industry, provided by VPI. The locations of seismic and well data are indicated in Figure 1.

3.1. Seismic data

In the study area, more than 40,000 km of 2D seismic data with 2 km to 32 km spacing has been interpreted. Due to differences in acquisition dates from 1974 to 2012, the quality of the seismic data changes depending on the survey. However, in general, the quality of the seismic data is medium to good.

3.2. Well data

There are 18 wells used in the study area. Most of the wells are in the eastern part of the Nam Con Son basin, only 3 wells are in the Tu Chinh - Vung May basin. Bio-stratigraphic data from these wells are used to correlate the Top Pliocene, Top Late Miocene and Top Middle Miocene on seismic data across the study area (Figure 2).

4. Methodology

4.1. Identifying and classifying magmatic bodies from seismic data

In addition to seismic morphology and seismic facies analysis, the study used multiple

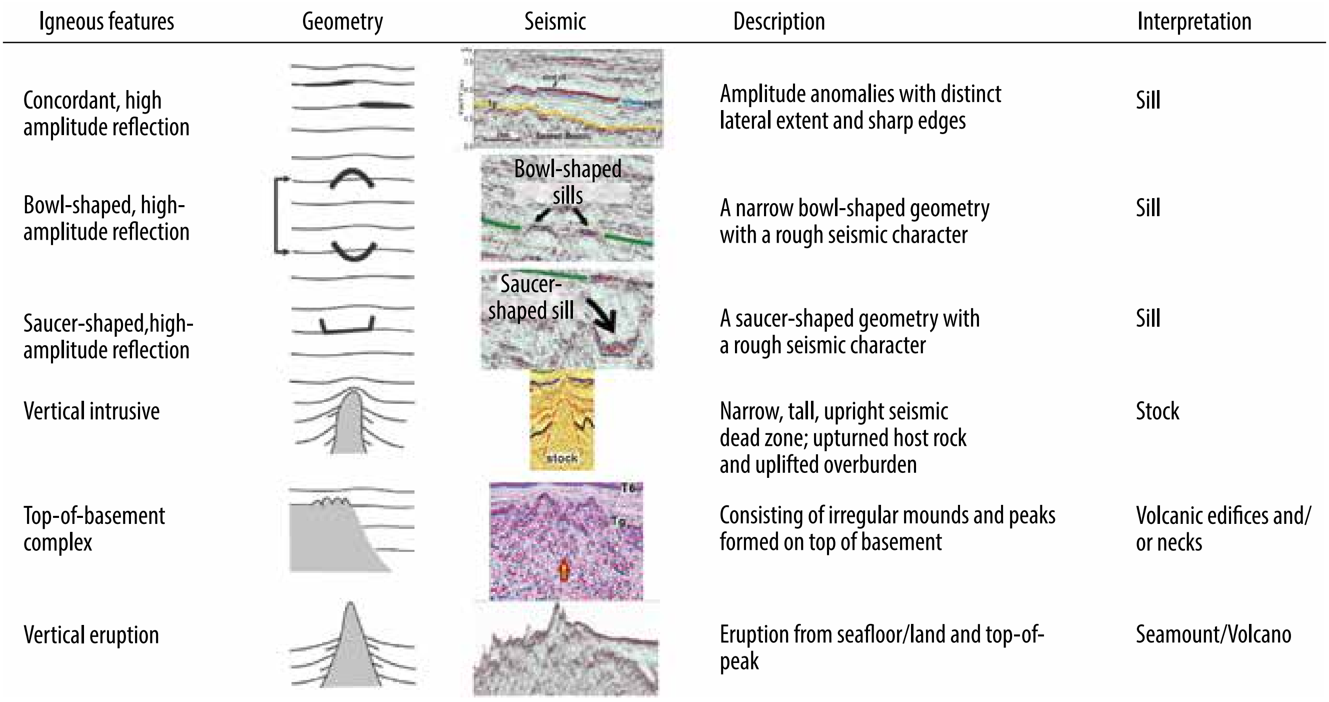


Figure 4. *Characteristics of magmatic bodies on seismic data [3].*

criteria to evaluate whether a seismic anomaly is a magmatic body (Figure 3). The intrusive bodies can be distinguished from gas anomalies and carbonate build-up/layers by identifying up-domed strata above the intrusive bodies, cross-cutting relationship, morphology and geological relationship with other extrusive bodies if present. Large intrusive bodies deform overlying strata by uplifting them during emplacement, thus creating a dome over the intrusive body, which is then onlapped by younger sediments during burial (Figure 5). Gas anomalies and carbonate deposits cannot deform overlying deposits in such manner. In addition, saucer-shaped bodies also cross-cut strata, which is completely different from gas anomalies and carbonate deposits. Last but not least, connection with other intrusive and extrusive bodies can put them in an overall framework, thus increasing the interpretation confidence.

Meanwhile, the extrusive bodies can be distinguished from gas anomalies and carbonate build-up/layers by morphology and geological relationship with other magmatic bodies. Cone-shaped features with inner transparent seismic reflection are very distinct from those of gas anomalies and carbonate platforms. They may look like carbonate mounds/reefs, but since these features in the study area were formed in deep-water settings, it is unlikely. Thus, the cone-shaped features and the surrounding high amplitude layers are interpreted as vents/volcanoes and lava sheets.

Well-defined magmatic bodies can be further divided into the following types based on morphology [14 - 16] (Figure 4):

- The intrusive: can be further divided into 2 types:

+ Sills: often exhibit high seismic amplitude due to the magmatic material having higher acoustic impedance contrast compared to the surrounding sediments. They usually cross-cut or are sub-parallel to country rock layering with many different shapes such as saucer shape and sheet (Figure 4).

+ Stocks: transparent reflection, with up-dragged surrounding strata, probably due to upward emplacement of the magmatic body (Figure 4).

- The extrusive:

+ Vents/volcanoes: cone-shaped, with chaotic reflection within the bodies. Onlap of surrounding strata due to later burial can be observed. Immediately below the vents/volcanoes there are usually columns of transparent seismic reflection, representing magmatic conduits from deeper levels. Lavas are often observed around vents/volcanoes.

+ Lavas: continuous and high amplitude, distributed around vents/volcanoes. Positive polarity across the seismic body indicates an increase in acoustic impedance. They are often found in topographic lows close to vents/volcanoes.

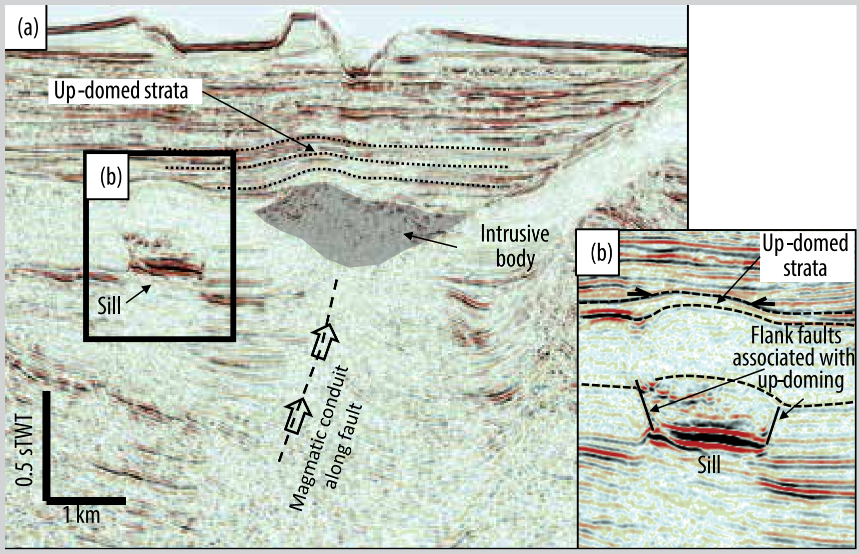


Figure 5. *Up-domed strata above an intrusive body due to its emplacement in the study area. The transparent zone under the intrusive body is not vertical, but rather dip at about 70 degrees. This suggest the control of syn-rift faults on magmatic conduit.*

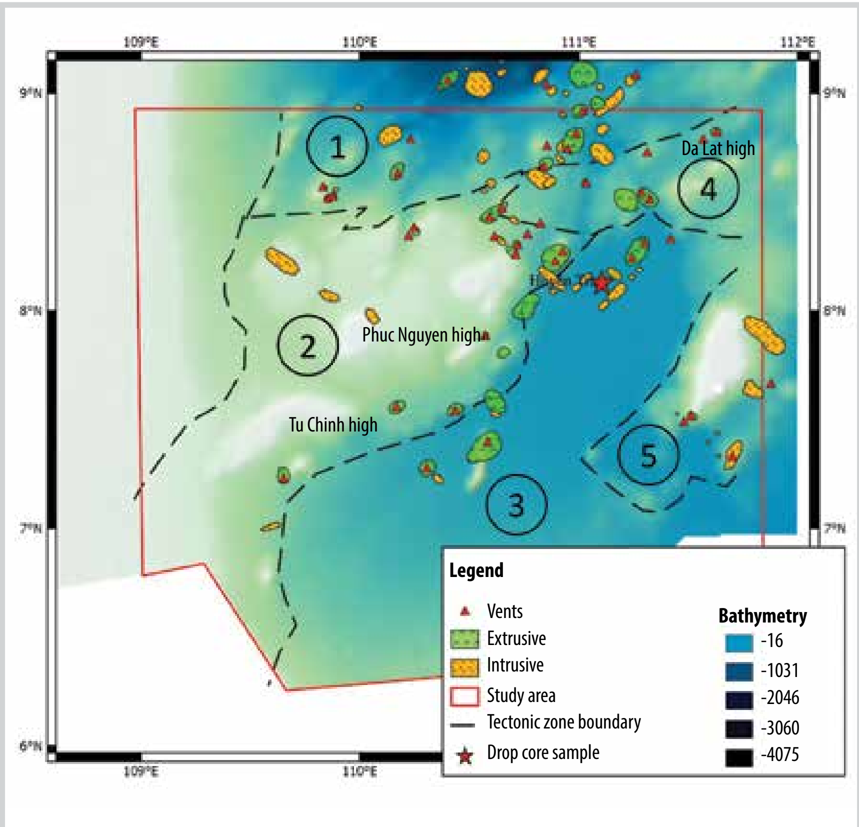


Figure 6. *Distribution map of Late Miocene-Quaternary magmatic activity in the Tu Chinh-Vung May basin and adjacent area overlain on modern bathymetry map. The tectonic zone division is based on the Top of pre-Cenozoic basement structural map: 1) East Sea spreading-influenced domain; 2) Tu Chinh high; 3) Vung May trough; 4) Da Lat-Da Tay differentiated high; 5) Vung May high. The magmatic distribution has a broad NE-SW trend.*

+ Eye-shaped vents: occasionally vent complexes can exhibit this shape, with concave down lower boundary. They have been attributed to country rock damage and collapsed due to explosive ejection of extrusive materials [14].

+ Conduits: column of chaotic or transparent seismic reflection, located immediately under vents/volcanoes or under sills. These conduits can be vertical or go along faults.

4.2. Dating intrusive and extrusive bodies

A common method to date the absolute age of magmatic rocks is the radiometric method. However, in the study area, very few seafloor samples and well samples are available, and these wells do not penetrate the identified shallow magmatic bodies. Therefore, we use cross-cutting relationship and stratigraphic relationship to relatively date these magmatic bodies. For extrusive bodies, the vents/volcanoes-lavas complex are dated as the stratigraphic interval containing the lavas. For intrusive bodies, they are dated younger than the stratigraphic interval that they intrude into. Occasionally, the age of intrusive bodies can be further constrained by identifying up-domed strata above the intrusive bodies (Figure 5).

5. Characteristics of magmatism in the study area

In the study area, a total of 16 intrusive and 14 extrusive clusters have been identified (Figure 6). For each magmatic cluster, more detailed features were identified like vents/volcanoes, lavas, sills, or conduits. These features are closely related in spatial arrangement:

- Sills often have conduits from deeper levels (Figures 5 and 7);

- Vents/volcanoes have conduits connecting with shallow sills, or from deeper levels within the pre-Cenozoic basement;

- Lavas are distributed around

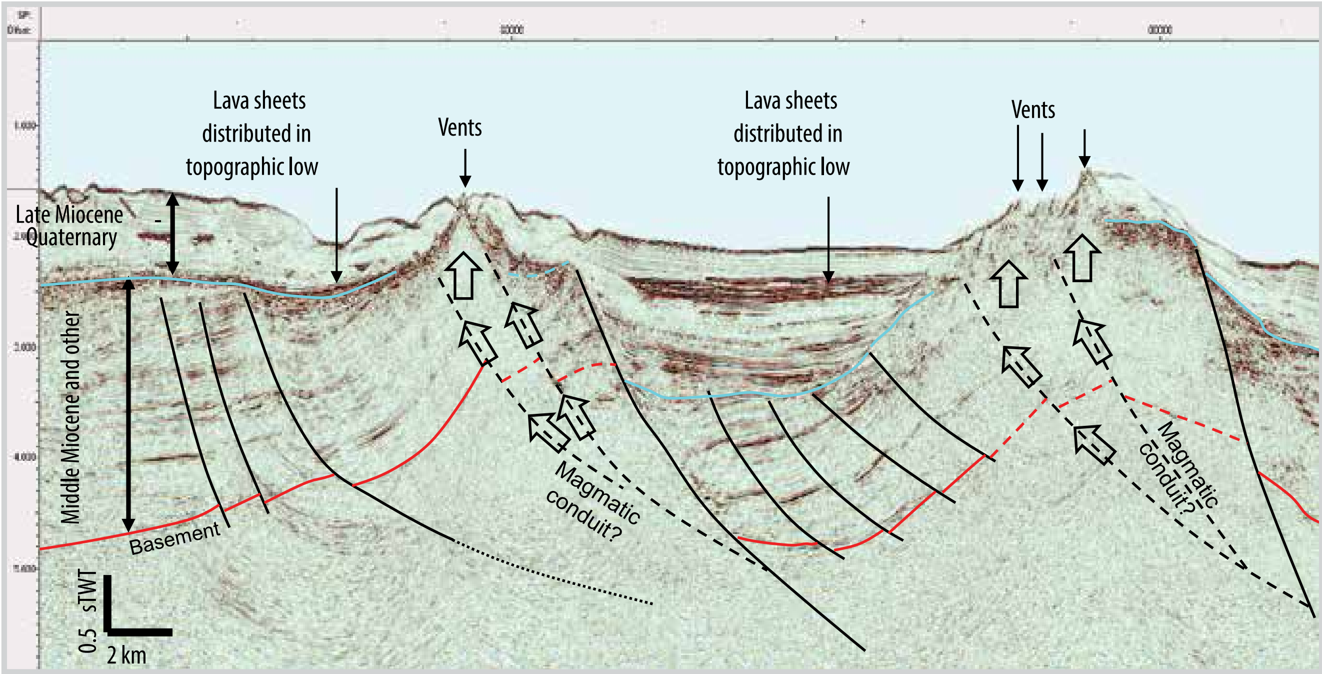


Figure 7. *A seismic section showing different types of extrusive bodies and accompanying transparent zones.*

vents/volcanoes and are constrained spatially by paleo-topography (Figure 7). Occasionally lavas are identified without vents/volcanoes, probably because vents/volcanoes lie between the relatively widely spaced 2D seismic lines;

- Conduits often follow syn-rift faults formed in the Middle Miocene or older, or are vertical in the Late Miocene - Quaternary section (Figure 8). This indicates the important role that old syn-rift faults have in controlling the magmatic pathway.

Sills, vents/volcanoes and lavas are the most common magmatic bodies in the study area. They are distributed in clusters with the same conduit system. The diameter of these clusters ranges from several km to tens of km, most commonly under 10 km.

Extrusive bodies are common in the East Sea spreading-influenced domain, Da Lat - Da Tay differentiated high and the margin around the Tu Chinh high. Their areas range from 10 to 150 km^2. Their thickness changes from 30 - 170 m, however due to the limit of the seismic data there might exist thinner extrusive bodies.

Intrusive bodies are identified in the East Sea spreading-influenced domain, north of the Vung May trough, part of the Vung May high and west of the Tu Chinh high. The area of these bodies changes from 15 to 170 km^2.

The age of these magmatic bodies ranges from Late Miocene to Quaternary. A couple of vents/volcanoes also extruded onto the modern seafloor.

Currently there are very few samples collected from young volcanoes in the study area. As a result, it is very difficult to predict their composition. Near-surface drop-core data of these bodies indicate that they contain vesicular basalt (Figure 9). However, there have not been any detailed studies on the petrography, geochemistry as well as origin of these samples.

6. Discussion

Some prior studies have mapped magmatic bodies at a large scale on the continental shelf of Vietnam [1]. Identification of magmatic bodies were primarily based on seismic characteristics and cross-cutting relationships, thus the seismic bodies are interpreted separately without context. Our study identifies these magmatic bodies based on multiple criteria such as seismic characteristics, associated deformation and cross-cutting relationship, morphology, geological settings, as well as linkage to other magmatic bodies (Figures 7 and 8). Once the linkage and relationship between different magmatic bodies are identified, interpretation uncertainties for the whole magmatic complex will be reduced.

The morphological and distribution characteristics of magmatic bodies in the Tu Chinh - Vung May basin

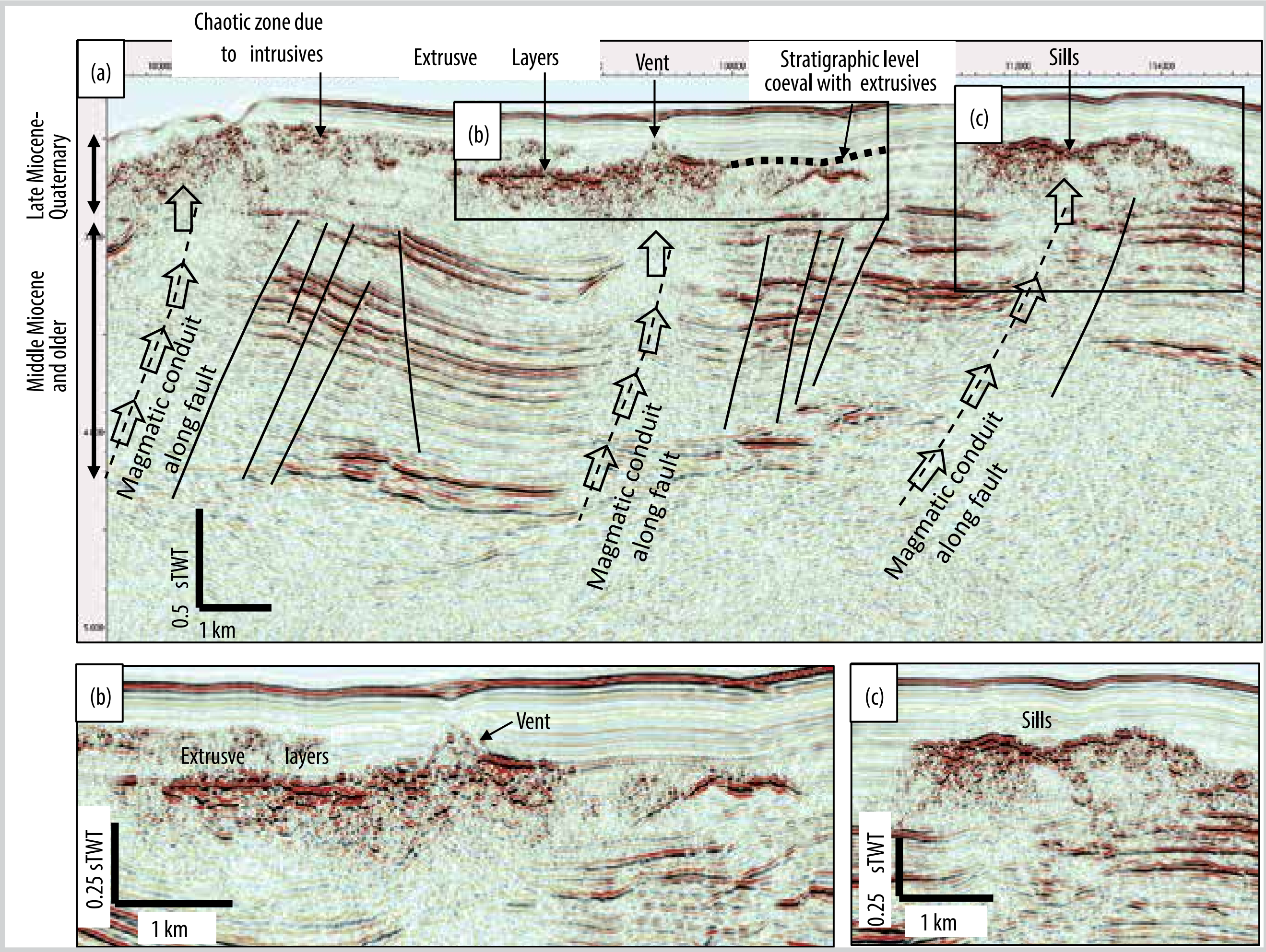
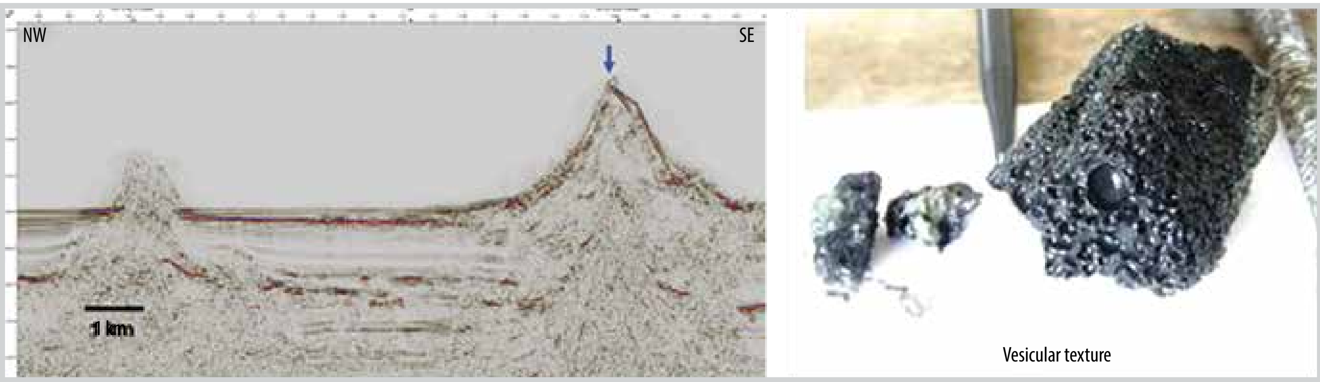


Figure 8. *Magmatic bodies and their relationship in the study area. a) Overall section showing the relationship between different magmatic bodies. b) Close-up section showing the characteristics of vents and extrusive layers. c) Close-up section showing the characteristics of intrusive bodies.*



(a) (b)

Figure 9. *(a) Seismic section across a volcano on the seafloor with the location of the drop-core site (blue arrow). (b) Vesicular basalt sample collected from the drop-core operation. Location of the sample is indicated on Figure 5. Source: Petrovietnam confidental report.*

and adjacent areas have many things in common with magmatic bodies in other areas of the East Sea. The intrusive bodies are often saucer-shaped or sheet-like sills while extrusive bodies are commonly vents/volcanoes surrounded by lavas [3]. Occasionally, seamounts on the seafloor can be identified with height up to several km (Figure 9). These magmatic bodies also distribute around conduit systems that follow syn-rift faults in deeper levels, and travel vertically in shallower section (Figure 8), as encountered in the Qiongdongnan and Hoang Sa basins [12, 16]. In addition, the mapped magmatic distribution has a broad NE-SW trend (Figure 6), which is consistent with that of old syn-rift faults. These syn-rift faults formed in response to regional extension during the Cenozoic associated with the East Sea seafloor spreading, thus many of them are large-scale listric faults that may control the pathway for magmatic materials from deep crustal level during the Miocene-Quaternary.

Most of the magmatism in the study area occurred during the Late Miocene-Quaternary. They cut across the Middle Miocene Unconformity (MMU), which is a regional unconformity that marks the end of regional rifting [3, 7]. This magmatic timing is consistent with widespread post-spreading magmatism in the East Sea, including the oceanic crust domain and the hyper-extended crust margin [3, 17]. This post-spreading magmatism also coincides with widespread basaltic magmatism onshore, particularly in the South Central Vietnam [9, 10], Hainan island and the Leizhou peninsula [17]. Therefore, this post-spreading magmatism is widespread on a regional scale, not only in the East Sea but also in the Indochina continental block and adjacent areas.

7. Conclusion

Based on the interpretation of about 40,000 km of 2D seismic data integrated with well data provided by VPI, the authors have identified 16 intrusive and 14 extrusive clusters in the Tu Chinh - Vung May basin and adjacent areas. Multiple criteria are used to identify the magmatic bodies including seismic characteristics, cross-cutting relationship, deformation of overlying strata, morphology and geological relationships. The intrusive bodies are often saucer-shaped or sheet-like sills, while the extrusive bodies are dominantly cone-like vents/volcanoes or sheet-like extrusive layers. The intrusive and extrusive bodies are often distributed in clusters with one or more common conduits. Magmatic conduits typically follow NE-SW trending syn-rift faults that formed during the Cenozoic basin formation and seafloor spreading in the East Sea. This is consistent with the broad NE-SW trend of magmatic distribution. Magmatic bodies are more abundant near the East Sea seafloor-spreading margin.

Uncertainties in interpretation can be further reduced through integrated magnetic-seismic analysis. Further studies should focus on detailed magnetic analysis to refine and update the currently identified magmatic bodies.

Magmatism is most intense and widespread in the Late Miocene - Quaternary in the study area in particular, and in the East Sea and adjacent areas in general. These activities occurred after continental rifting and seafloor-spreading had ended, which is characteristic of magma-poor margins. Further studies focusing on the petrography, geochemistry and origin of these magmatic bodies are needed to clarify their roles in the metallogeny of deep-water solid mineral resources in the East Sea.

References

[1] Trịnh Xuân Cường và nnk, "Thu thập, phân tích, tổng hợp các tài liệu về khí hydrate để xác lập các dấu hiệu, tiền đề về tiềm năng khí hydrate ở các vùng biển và thềm lục địa Việt Nam", Viện Dầu khí Việt Nam, 2016.

[2] Lê Chi Mai và nnk, "Đặc điểm trầm tích nước sâu tầng cấu trúc post-rift và triển vọng dầu khí của chúng trong khu vực Nam bể Phú Khánh, Đông Nam bể Nam Côn Sơn và bể Tư Chính - Vũng Mây", Viện Dầu khí Việt Nam, 2019.

[3] Xiaoxiao Song, Chun-Feng Li, Yongjian Yao, and HeshengShie, "Magmatism in the evolution of the South China Sea: Geophysical characterization", *Marine Geology*, Vol. 394, pp. 4 - 15, 2017. DOI: 10.1016/j.margeo.2017.07.021.

[4] Michael B.W. Fyhn, Boldreel Lars O. Boldreel, and Lars H. Nielsen, "Geological development of the Central and South Vietnamese margin: Implications for the establishment of the South China Sea, Indochinese escape tectonics and Cenozoic volcanism", *Tectonophysics*, Vol. 478, No. 3 - 4, pp. 184 - 214, 2009. DOI: 10.1016/j.tecto.2009.08.002.

[5] C.K. Morley, "Major unconformities/termination of extension events and associated surfaces in the South China Seas: Review and implications for tectonic development", *Journal of Asian Earth Sciences*, Vol. 120, pp. 62 - 86, 2016. DOI: 10.1016/j.jseaes.2016.01.013.

[6] VPI and PVEP-POC, *Structural-tectonic model study for Block 05-1a*, 2019.

[7] Franke Dieter, Savva Dimitri, Pubellier Manuel, Stephan Steuer, Benoit Mouly, Jean-Luc Auxietre, Florian Meresse, and Nicolas Chamot-Rooke, "The final rifting evolution in the South China Sea", *Marine and Petroleum*

Acknowledgement: *The authors express their sincere gratitude for the support of the national research project "Studying the pre-conditions and indications for exploring solid mineral resources in the deep-water Tu Chinh - Vung May area" (KC 09.40/16-20) during the research and completion of this work.*

Geology, Vol. 58, pp. 704 - 720, 2014. DOI: 10.1016/j.marpetgeo.2013.11.020.

[8] Savva Dimitri, Pubellier Manuel, Franke Dieter, Nicolas Chamot-Rooke, Florian Meresse, Stephan Steuer, and Jean-Luc Auxietre, "Different expressions of rifting on the South China Sea margins", *Marine and Petroleum Geology*, Vol. 58, pp. 579 - 598, 2014. DOI: 10.1016/j.marpetgeo.2014.05.023.

[9] Nguyen Hoang and Martin Flower, "Petrogenesis of Cenozoic basalts from Vietnam: Implication for origins of a "Diffuse igneous province"", *Journal of Petrology*, Vol. 39, No 3, pp. 369 - 395, 1998. DOI: 10.1093/petroj/39.3.369.

[10] Nguyễn Hoàng, Martin F.J. Flower, Cung Thượng Chí, Phạm Tích Xuân, Hoàng Văn Quý, and Trần Thanh Sơn, "Collision-induced basalt eruptions at Pleiku and Buon Me Thuot, south-central Viet Nam", *Journal of Geodynamics*, Vol. 69, pp. 65 - 83, 2013. DOI: 10.1016/j.jog.2012.03.012.

[11] Fang Zhao, Tiago M. Alves, Wu Shiguo, Li Wei, Mads Huuse, Lijun Mi, Qiliang Sun, and Benjun Ma, "Prolonged post-rift magmatism on highly extended crust of divergent continental margins (Baiyun Sag, South China Sea)", *Earth and Planetary Science Letters*, Vol. 445, pp. 79 - 91, 2016. DOI: 10.1016/j.epsl.2016.04.001.

[12] Lijie Wang, Zhen Sun, Jinhai Yang, Zhipeng Sun, Jitian Zhu, Haiteng Zhuo, and Joann Stock, "Seismic characteristics and evolution of post-rift igneous complexes and hydrothermal vents in the Lingshui sag (Qiongdongnan basin), Northwestern South China Sea", *Marine Geology*, Vol. 418, 2019. DOI: 10.1016/j.margeo.2019.106043.

[13] Quanshu Yan, Xuefa Shi, and Paterno R. Castillo, "The Late Mesozoi-Cenozoic tectonic evolution of the South China Sea: A petrologic perspective", *Journal of Asian Earth Sciences*, Vol. 85, pp. 178 - 201, 2019. DOI: 10.1016/j.jseaes.2014.02.005.

[14] S. Planke, T. Rasmussen, S.S. Rey, and R. Myklebust, "Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins", *Petroleum Geology North-West Europe and Global Perspective*, Vol. 6, pp. 833 - 844, 2005. DOI: 10.1144/0060833.

[15] Qiliang Sun, Christopher A.L. Jackson, Craig Magee, Samuel J. Mitchell, and Xinong Xie1, "Extrusion dynamics of deepwater volcanoes revealed by 3-D seismic data", *Solid Earth*, Vol. 10, No. 4, pp. 1269 - 1282, 2019. DOI: 10.5194/se-10-1269-2019.

[16] Guoping Zuo and Guozhang Fan, "A study of volcanic rocks identification by seismic methods in Subei basin, Jiangsu province, China", *AAPG Annual Convention and Exhibiton, Houston, Texas*, USA, 10 - 13 April 2011.

[17] Pin Yan, Hui Deng, Hailing Liu, Zhirong Zhang, and Yukun Jiang, "The temporal and spatial distribution of volcanism in the South China Sea region", *Journal of Asian Earth Sciences*, Vol. 27, No. 5, pp. 647 - 659. DOI: 0.1016/j.jseaes.2005.06.005.