RESEARCH PAPER

Palynostratigraphy, palynofacies, and reservoir characteristics of upper Oligocene − lower Miocene sediments in the southwestern Cuu Long Basin, Vietnam

Mai H. Dam [a,c,d,*], Tran V. Xuan [c,d], Nguyen T. Trieu [b], Vu T. Tuyen [b], Nguyen T. Tham [a], Bui T.N. Phuong [b], Pham T. Duyen [a], Nguyen T. Tuyen [a], Nguyen X. Kha [c,d], Dinh V. Cuong [c,d,e], Nguyen Tuan [c,d], Truong Q. Thanh [c,d]

[a] Department of Biostratigraphy, Analysis Laboratory Center, Vietnam Petroleum Institute, Viet Nam
[b] Department of Petrography and Sedimentology, Analysis Laboratory Center, Vietnam Petroleum Institute, Viet Nam
[c] Faculty of Geology and Petroleum Engineering, Ho Chi Minh City University of Technology, Viet Nam
[d] Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc City, Viet Nam
[e] Department of Production, Development and Production Division, PetroVietnam Exploration Production Corporation, Vietnam Oil and Gas Group, Ho Chi Minh City, Viet Nam

Abstract

In the early stages of oil and gas exploration in Vietnam, studies on rock samples from exploratory wells provide essential information to forecast the hydrocarbon potential and feasibility of the project. These are premise studies of the upstream segment. This study provides a detailed stratigraphy, depositional environment, rock properties related to reservoir quality, and prediction of hydrocarbon generation potential in the southwestern Cuu Long Basin. Palynology, palynofacies, thin section, radiography diffraction, and scanning electron microscopy methods were done in stratigraphic and sedimentological studies at the upper Oligocene-lower Miocene clastic sedimentary rocks, corresponding to the Bach Ho and Tra Tan formations, respectively. Research result shows that the sediment of the Tra Tan Formation was deposited mainly in a freshwater lacustrine environment and was good in organic matter with good hydrocarbon generation potential, the porosity of the rock was assessed as poor in the lower Tra Tan and moderate to very good in the upper Tra Tan Member. The Bach Ho Formation was characterized by two sedimentary cycles with various environments from freshwater plain to inner neritic. The Lower Bach Ho Member was poor in palynomorphs and organic matter and was deposited mainly in a freshwater fluvial environment with high energy conditions; its porosity was very good, whereas the Upper Bach Ho Member was abundant in palynomorphs and organic matter and was intercalated by condensed sections that were the seals for the entire Cuu Long Basin.

Keywords: Cuu Long Basin, Depositional environment, Palynofacies, Palynology, Reservoir quality, Upper Oligocene-lower Miocene

1. Introduction

The Cuu Long Basin is a sedimentary basin containing hydrocarbons mainly on the continental shelf of Vietnam and was filled with Cenozoic sediments (Fig. 1). The objects of petroleum study in clastic sedimentary rocks are mainly lower Miocene and Oligocene formations.[1,2] Recently, studies on stratigraphy, sedimentary environment, and petrographic properties were carried out in detail in all upstream activities because they greatly influence the geological structure models of the field, forecasting hydrocarbon reserves of the Cuu Long Basin; therefore, they have been studied and evaluated very

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* Corresponding author.
E-mail address: dammh@vpi.pvn.vn (M.H. Dam).

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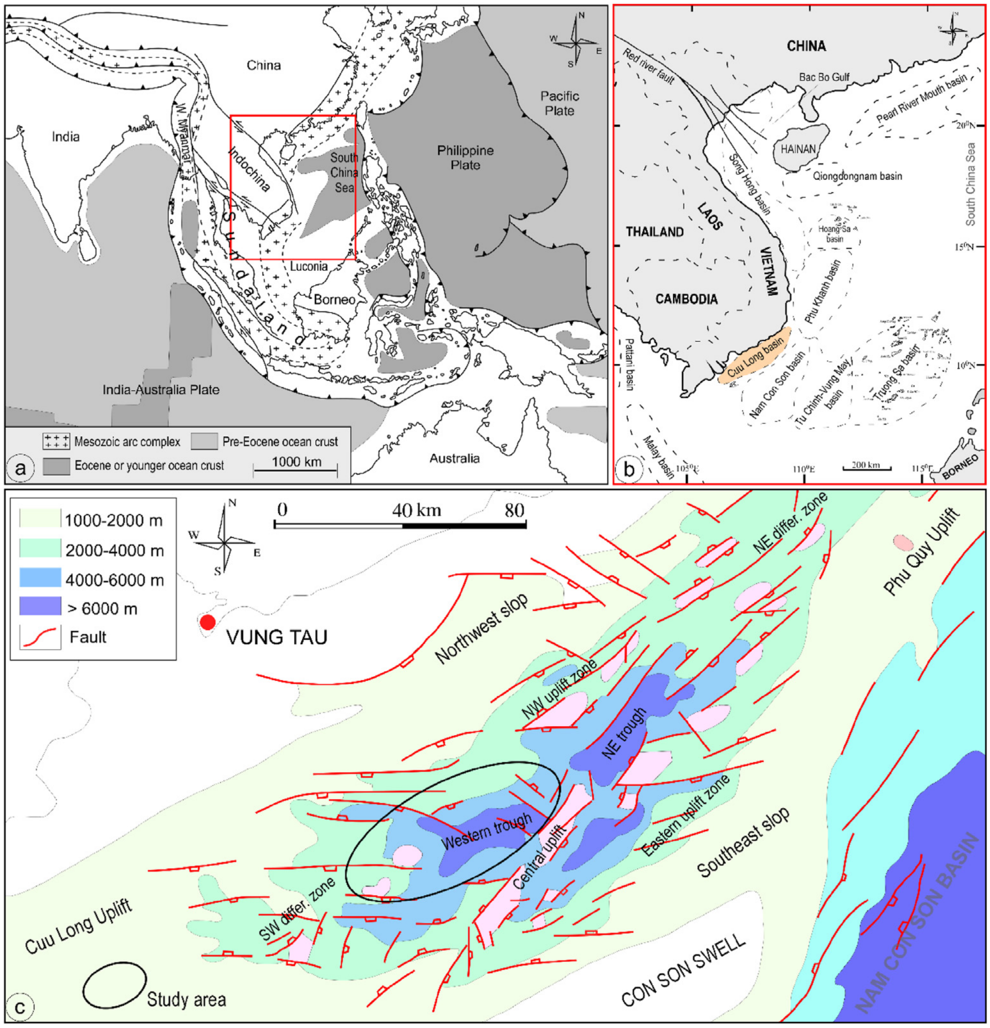

Fig. 1. (a) Vietnam's structural outline of the SE Asian area, (b) The sedimentary basins on the Vietnam continental shelf and adjacent areas, (c) the study area of the Cuu Long Basin.

carefully to restrict the risks. In particular, updating stratigraphic boundaries is always done regularly because the stratigraphic boundary can change when discoveries about geological events, fossil evidence, biological traces, or markers are made. From 2004 to the present, the results of stratigraphic and sedimentological studies were updated frequently by new analysis from the wells, with the stratigraphic column established from the Eocene to the Quaternary of the Cuu Long Basin.[2,3] The stratigraphic boundaries were interpreted by biostratigraphy, lithology, seismic stratigraphy, and wireline logs methods and correspondingly named with seismic reflection surfaces from "Letter A-F" (Fig. 2).[2–5] According to previous studies in the western Cuu Long Basin,[6,7] a sedimentary section named Bach Ho 5.2 was classified as the lowest part of the lower Miocene by interpreting wireline logs and seismic stratigraphy; however, the biostratigraphic studies have found palynomorph assemblages older than the Miocene (Fig. 3).[8–10] Therefore, understanding the biostratigraphic characteristics, sedimentary deposition, hydrocarbon potential, and reservoir properties of the lower Miocene-upper Oligocene sediments in the southwestern Cuu Long Basin becomes a matter of urgency. This study aims to investigate detailed stratigraphy and lithological properties to clarify the characteristics of lower Miocene – upper Oligocene sediments and their significance in petroleum systems, geological structure modeling, and forecasting hydrocarbon reserves in the studied area.

2. Geological settings

The study area is located in the southwestern region of the Cuu Long Basin which is an early Cenozoic rift basin located on the southeast continental shelf of Vietnam (Fig. 1). The basin evolution was divided into three main periods.[2,5,11–13] Pre-rift, occurring from Triassic to Paleocene periods, this

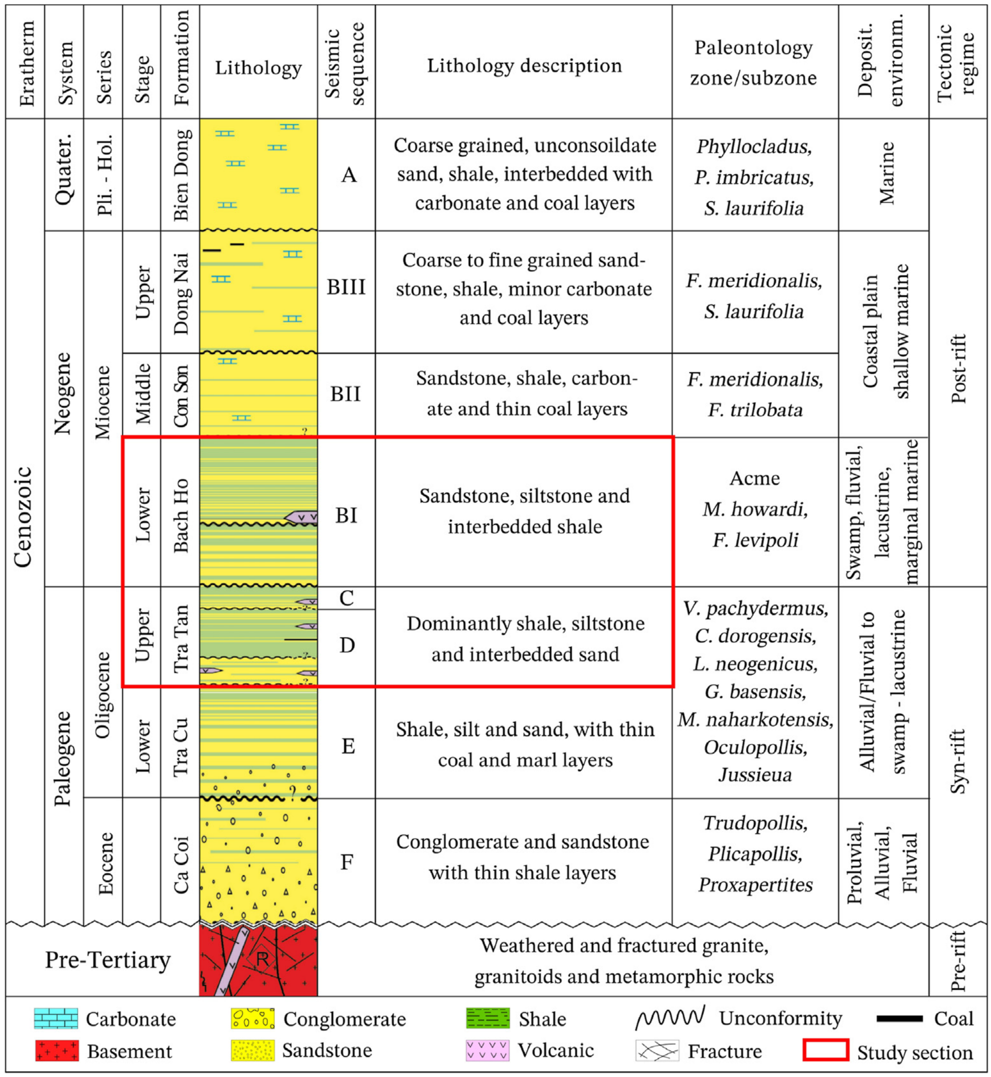

Fig. 2. General stratigraphic column of the Cuu Long Basin.[2]

phase was the stage of emplacement of the Pre-Cenozoic basement rocks that consist of the Hon Khoai (T-J_1), Dinh Quan (J_2-K_1), and Ca Na (K_2-Pg) complexes.[14,15] The Palaeocene was the time of weathering, peneplanation, and erosion of basement rocks in the Cuu Long Basin;[13] Syn-rift occurred in the Eocene-Oligocene period and was related to extensional tectonic activities, rifting, and the creation of grabens and half grabens which were filled with Eocene - early Oligocene sediments during the early rift stage; Post-rift, beginning from the early Miocene to the present, this was a period of stable thermal subsidence and marked widespread marine intrusion by the Rotalia bed, forming a reliable stratigraphic marker and regional seal in the latest early Miocene. Cenozoic sediments directly covered pre-Cenozoic basement rocks that were eroded and weathered. The characteristics of each stratigraphic unit are shown in the general stratigraphic column of the Cuu Long Basin (Fig. 2).

3. Materials and methods

The materials were collected from the Vietnam Petroleum Institute and the Vietnam Oil and Gas Group, including 22 wells that were carried out from 2004 to 2022. The ditch-cutting, sidewall core, and core samples were used for palynology, palynofacies, and sedimentary petrology studies and were analyzed at the Analysis Laboratory Center, Vietnam Petroleum Institute.

3.1. Palynological and palynofacies analysis

The palynological slides were observed under a biologically transmitted light microscope at

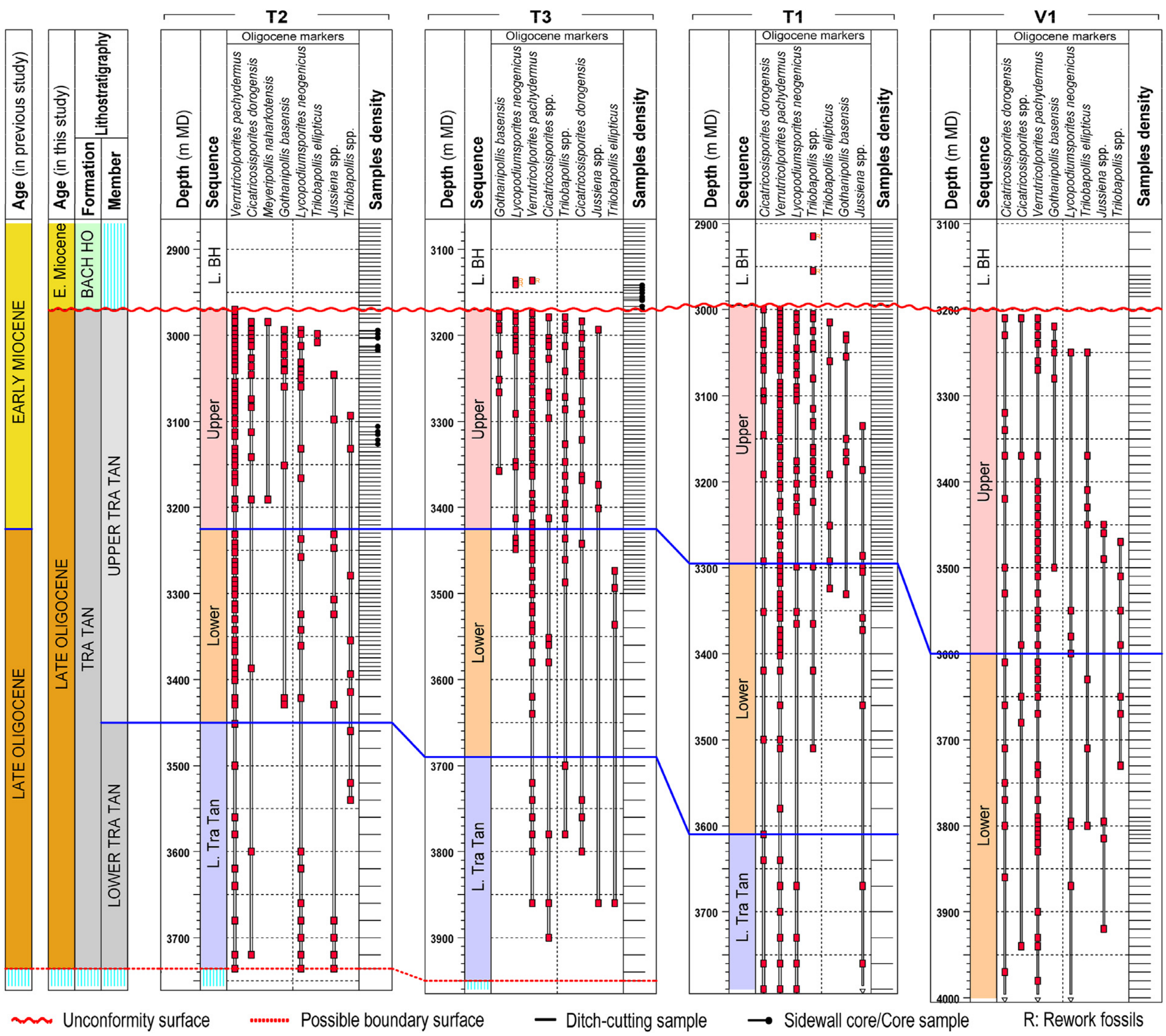

Fig. 3. The marker sporomorphs are not younger than Oligocene in the studied wells.

magnifications of 20×−100×. The palynomorphs were identified based on their structural and morphological characteristics and were compared with the palynozonal framework in Southeast Asia and adjacent regions.[4,16−21] Analysis results were recorded by counting in the full slide. Palynofacies analysis involves the identification of palynomorph, phytoclast/palynomaceral (PM), and amorphous organic matter (AOM).[22−28,37,38] They were carried out based on the percentage of particulate organic matter by counting 200 fields of view from each sample, categorised by Tyson.[26,28,37,38]

3.2. Petrographical analysis

Petrographical studies include thin section, scanning electron microscopy (SEM), and radiography diffraction (XRD) analysis to interpret the parameters of the sedimentary source, rock classification, stages of diagenesis, depositional environment, and reservoir quality. Thin sections were studied under a polarised microscope to determine the mineral composition, texture, and rock classification. The framework grain and visible porosity were established via modal analysis by counting 300−500 points per thin section.[29−33] The SEM method provided a three dimensional view of the high magnification of pores and the distribution of authigenic phases. It identified and assessed the morphology, type of authigenic minerals, and their relationship with framework grains and pore networks.[34] The XRD analysis that ran parameters the generator setting at 40 mA and 40 kV, using Cu−Kα radiation with a Ni filter, step size of 0.010°, and time scale of 0.2 s provided the powder diffraction parameters to identify the authigenic clay minerals and their relationship.[35,36,39]

4. Results and discussion

4.1. Sedimentary characteristics of the Tra Tan Formation, upper Oligocene

The Tra Tan formation was widely distributed in the Cuu Long Basin. Its late Oligocene age is determined by the occurrence of marker sporomorphs in the sedimentary rocks. The upper boundary of the formation was always found *Verrutricolporites pachydermus, Lycopodiumsporites neogenicus, Cicatricosisporites dorogensis, Gothanipollis basensis, Trilobapollis elipticus, Meyeripollis naharkotensis, Jussieua* spp. fossils that are not younger than the Oligocene (Fig. 3, Appendix A (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1)). The lower boundary of the formation is defined by the first appearance of *V. pachydermus* pollen which is not older than the Late Oligocene. The sediment of the Tra Tan formation contained abundant freshwater algae assemblages and was deposited mainly under freshwater lacustrine conditions, varying from shallow to deep water settings. The Tra Tan was divided into two parts by the characteristics of palynomorphs.

4.1.1. Palynostratigraphy and palynofacies

4.1.1.1. Lower Tra Tan member. Palynomorph assemblage record is not abundant, consisting mainly of freshwater algae and fern swamps. Based on the quantity and distribution of palynomorphs, the study area was divided into the northeastern, southeastern, and western margin areas.

In the northeast, sedimentary thickness reached 660 m. The palynomorph assemblage is characterised by freshwater algae, peat swamps, and freshwater spores. The predominance of *Botryococcus* algae accounts for 85% of the total palynomorphs, indicating the existence of paleolakes which were deposited between the shoreface and shallow lakes (Fig. 4). In the southeast, the freshwater algae account for 80−95% of the total palynomorphs, with a predominance of *Bosedinia* and a small amount of *Pediastrum*, suggesting sedimentary

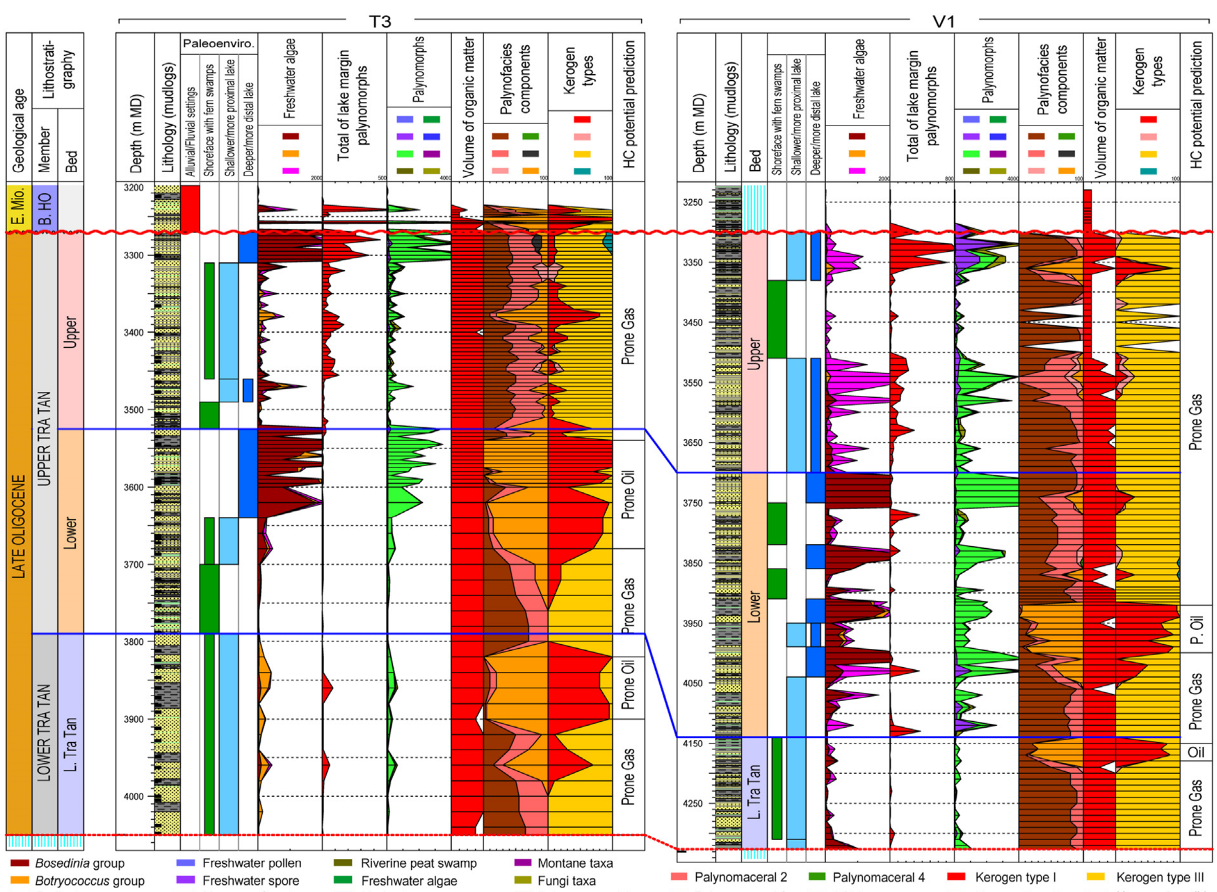

Fig. 4. Characteristics of the palynomorphs and palynofacies, hydrocarbon potentials prediction of the Tra Tan formation in the northeast (T3) and southeast (V1) of the study area.

deposition under deep lake conditions. The sedimentary thickness was ~650 m. The member in the western margin area was the thinnest thickness (around 50 m), directly covering the crystalline basement rocks. The freshwater algae fluctuate from 30 to 60% of the total palynomorphs and consist of *Bosedinia, Botryococcus,* and *Pediastrum*, predominately *Botryococcus* (50–80% of the total algae), suggesting the depositional environment in more proximal lake settings. The organic matter is very good in volume and consists of PM 1, AOM, PM 2, and a high rate of freshwater algae indicating potential source rocks with kerogen types I and III prone to oil and gas production, respectively (Fig. 4).

4.1.1.2. Upper Tra Tan member. The Upper Tra Tan Member was widely distributed in the research wells, with a thickness of 70 m at the western margin and over 1000 m in the central and eastern areas. The palynological assemblage is extremely abundant freshwater algae, accounting for over 90% of the total palynomorphs. The upper Tra Tan member was divided into two distinct sedimentary cycles (Fig. 4). The lower section of the member was extremely abundant palynomorphs. This cycle is considered the acme cycle of freshwater algae in the entire Cuu Long Basin, with the predominance of *Bosedinia* reaching over 95% of the total algal fossils and the remainder being *Botryococcus* in the lower interval of this cycle. The upper section of the member is the second acme cycle of freshwater algae. *Bosedinia* decreased moderately and was replaced by *Pediastrum* and *Botryococcus*. These changes reflect the depositional conditions related to the tectonic activities that were the uplift of the study area. Furthermore, aquatic spores such as *Magnastriatites howardi* and lake margin pollen of *Barringtona* and *Lagerstroemia* are abundant during this period, indicating that the depositional environment tended to gradually shallower towards the end of the Oligocene and have a stratigraphic hiatus at the top of Oligocene (Fig. 4). In previous studies,[8,10] this section was identified as the lowest part of the Early Miocene. However, this study result shows that this section contains Oligocene marker palynomorphs with a thickness of up to 400 m. The top of this sedimentary section shows significant changes in the quantity, composition of palynomorphs, and the depositional environment (Figs. 3 and 4). Moreover, the sediments covering the top of this section are very poor in palynomorphs. Therefore, the authors hypothesise that the unconformity surface which is the boundary between the Miocene and Oligocene may exist at the top of the Upper Tra Tan Member. Hence, the authors propose classifying this section as the highest part of the Tra Tan Formation, corresponding to the Late Oligocene. This is a finding of stratigraphic boundary change in the study area. The organic matter of the Upper Tra Tan Member is good in volume, mainly composed of AOM, PM 1, and PM 2. The lower part of the member contains a high proportion of AOM (40–70%) and freshwater algae (over 90%), corresponding to kerogen type I with the oil-prone and oil-gas mixture, while the upper part consists mainly of PM 1 and PM 2 with a high proportion (70–90%), corresponding to kerogen type III, predominate gas prone, and gas-oil mixture.

4.1.2. Sedimentary petrography characteristics

4.1.2.1. Lower Tra Tan member. The petrographic composition includes mostly sandstone and claystone/silty claystone. Sandstones are classified mainly as arkose with lithic arkose and feldspathic greywackes. The texture characteristic and mineral composition of the rock are shown in Appendix B (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) (Fig. 5a). The XRD analysis results for the clay fraction in

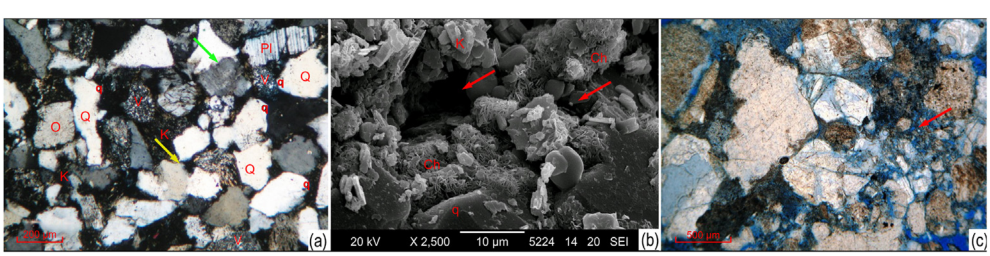

Fig. 5. Thin section and scanning electron microscopy photographs of the lower Tra Tan member. (a) The mineral composition comprises mostly quartz (Q), orthoclase (O), plagioclase (Pl), granite (G), volcanic (V), kaolinite (K), quartz overgrowth (q), mainly point-to-point (yellow arrows), long (green arrow); (b) Detrital feldspar grain has been partly dissolved and forming secondary pores (red arrows). Illite/Smectite (I/S) occurred with mainly crenulated morphology, intermixing with platy chlorite flakes (Ch); (c) Well-preserved primary porosity (red arrows) and a few secondary porosities.

Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) show that smectite is present at a low rate in some samples, indicating that the rock was altered during mesodiagenesis.

As the analysis results, the sandstone is considered clean and related to the alluvial/fluvial plain of the lacustrine environment settings. High levels of authigenic minerals, such as quartz, albite, calcite, and other clay minerals (Fig. 5a). Authigenic quartz developed from primary quartz grains partly filled up pore throats; kaolinite filled up the primary pores and divided them into micropores. Calcite authigenic occurred locally in poikilotopic types, which strongly affected the permeability of rocks (Fig. 5a). The SEM analysis result shows that kaolinite authigenic filled up the primary porosity and divided them into many micropores, with ribbon illite clays often coated on the pore throat walls or bridged pore throats (Fig. 5b). The XRD result for the clay fraction in Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) shows that smectite is present at a low rate, indicating that the rock was altered during mesodiagenesis. The porosity network is strongly affected mainly by quartz authigenic and its distribution was heterogeneous due to the local appearance of detrital matrix clay minerals and poikilotopic calcite. Generally, the porosity of the Lower Tra Tan is not good, mainly primary porosity (5.2–16.0%, porosity measured, 50–150 μm) and secondary porosity which was created by the dissolution of unstable detrital grains such as feldspar (<1.0%, porosity measured, 2–20 μm) (Fig. 5c).

4.1.2.2. Upper Tra Tan member

4.1.2.2.1. The lower section of the upper Tra Tan member. The petrographic composition of this section includes sandstones, claystones, and siltstones. Sandstones are classified as main arkose, lithic arkose, or feldspathic greywacke. The texture characteristics and mineral composition of the rock are shown in Appendix B (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1). The XRD analysis result for the clay fraction in Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) reveals that the absence or a very low rate of the smectite could be altered into illite-smectite due to the hydrothermal process, indicating in the early mesodiagenesis stage with fair to high-level textural maturity. The sandstone is considered clean and deposited in environment-related freshwater lacustrine conditions. Authigenic minerals contain reasonably high levels of quartz, albite, pyrite, zeolite, calcite, and other clay minerals. Authigenic quartz developed from primary quartz grains partly filled up pore throats; kaolinite filled up the primary pores and divided them into micropores. Calcite authigenic occurred locally in poikilotopic types that strongly affected the permeability of rocks (Fig. 6a). SEM analysis reveals quartz overgrowth filling the pore spaces and pore throats. Chlorite minerals are commonly oriented on the edges, with a face

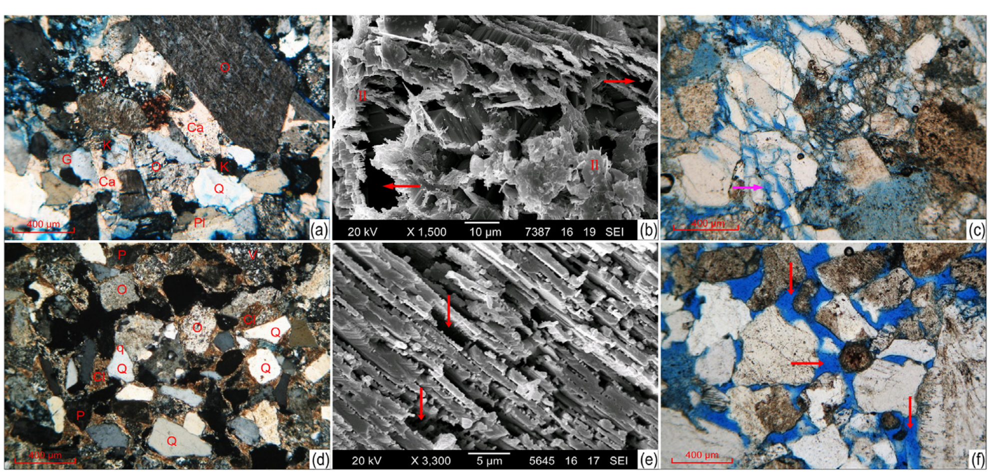

Fig. 6. Thin section and scanning electron microscopy photographs in the Upper Tra Tan. (a) The mineral composition comprised quartz (Q), orthoclase (O), plagioclase (Pl), granite (G), and volcanic (V). Authigenic minerals such as kaolinite (K), quartz overgrowth (q), and calcite (Ca); (b) Feldspar grains have been partly dissolved to form secondary pores (red arrows); (c) Visible porosity is not good because it is affected by the process of compaction and filling by authigenic kaolinite mineral; (d) Matrix clay fills the pore spaces, destroying the entire porous system; (e) The dissolution of feldspar grains creates secondary porosity (red arrows); (f) Porosity is good with sizes ranging from 100 to 200 μm (red arrows).

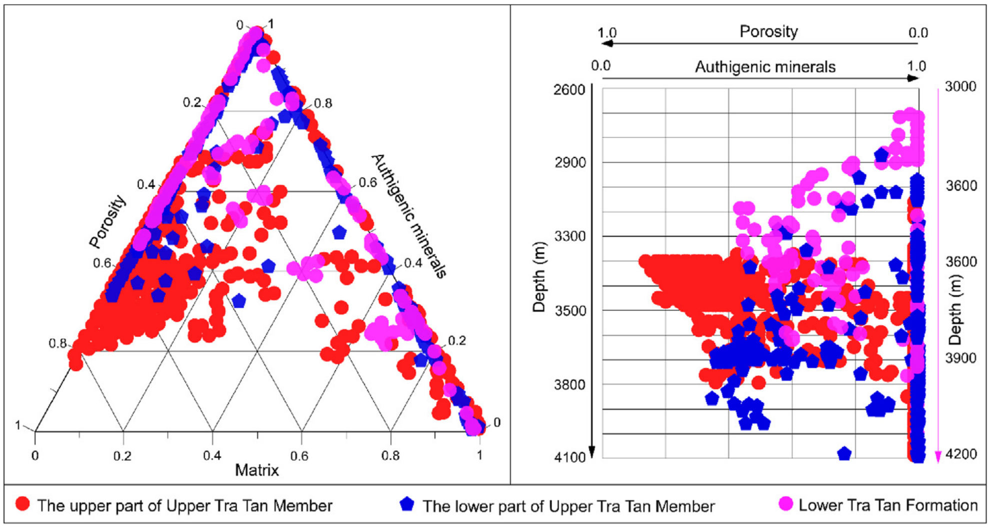

Fig. 7. (a) Relationship of detrital matrix clay and authigenic minerals with the porosity in the Tra Tan formation; (b) Relationship between authigenic minerals and the porosity of the Tra Tan formation.

perpendicular to the detrital grain surfaces. Kaolinite aggregates are covered by authigenic illite/chlorite (Fig. 6b). Generally, the porosity of these sediments is poor, mainly primary porosity (5.0−15.0%) (Fig. 6c) and is strongly affected by authigenic minerals, detrital matrix, and compaction or depth of formations (Fig. 7).

4.1.2.2.2. *The upper section of the upper Tra Tan member*. The lithological composition of this section includes mainly sandstone and a minimal amount of claystone and siltstone. The texture and mineral characteristics are shown in Appendix B (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1). The XRD analysis results for the clay fraction in Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) shows the presence of smectite in a low proportion, indicating that the rock entered the early stages of mesodiagenesis. The SEM analysis result indicates that authigenic kaolinite filled up the pore spaces between the detrital grains and micropores, reducing the rock's permeability. Feldspar grains were partly dissolved to create secondary pores (Fig. 6e). The reservoir quality is moderate to good (ranges 7−25%, porosity measured 30−250 μm) and sometimes very good at some wells of northeastern structures. The porosity is mainly intergranular pores and is enhanced by intragranular pores and micropores in clay clusters (Fig. 6f). The pore system was partially reduced by cement filling, such as calcite and zeolite minerals (Fig. 7).

4.2. *Sedimentary characteristics of the Bach Ho Formation, lower Miocene*

The Lower Miocene sediment of the Bach Ho Formation was distributed in the entire study area. The top of the formation is determined by the last occurrence of *Cribroperidinium granomenbranaceous*, *Apteodinium − Cribroperidinium* dinocysts, and *Sporotrapoidite* pollen. They identified a geological age no younger than the early Miocene. The palynomorph assemblage of the Bach Ho formation was divided into two clear parts, reflecting the differences in the depositional conditions.

4.2.1. *Palynostratigraphy and palynofacies*

4.2.1.1. *Lower Bach Ho member*. The palynomorph assemblage recovery in this member is very low, indicating that the sedimentary depositional environment is an alluvial/fluvial plain condition with a dry climate and riverine peat swamp condition near the shore with slight brackishwater influences. In the lower part, a sedimentary sequence contains abundant palynomorphs, including *Bosedinia infragranulata, Pediastrum, Botryococcus*, and *M. howardi* that characterize the depositional environment from shallow to deeper lake settings. Its thickness ranges from 20 m to 50 m with a fine-grained petrographic composition and is considered the local seal of the eastern region, whereas it is not found in the western area (Fig. 8). The Lower Bach Ho member is poor in organic matter, mainly composes of PM 1 and PM 2, indicating a sedimentary depositional environment under high-energy conditions.

4.2.1.2. Upper Bach Ho member. The upper Bach Ho member contains abundant and diverse palynomorphs and was divided into three varied sedimentary sections (Fig. 8). The lower section is low in palynomorph recovery with the reappearance of freshwater algae and swamp sporomorphs and was deposited in freshwater lacustrine and riverine/peat swamp environments. The middle section is characterized by the transition of the depositional environment from the freshwater lacustrine or riverine/peat swamp to the restricted marine environment. The upper section is characterized by a thick shale/claystone that contains an abundance of marine dinoflagellate and saccate pollen taxa (Fig. 8). In addition, an abundant assemblage of foraminifera (*Ammonia* species) was also found in this section and it is evidence for the first presence of marine sediment in the Cuu Long Basin. Its thickness ranges from 20 to 150 m and plays an important role in the petroleum system of the Cuu Long Basin. The organic matter is medium to good in volume and consists of mainly PM 1, PM 2, AOM, and some PM 4, indicating kerogen type III and type I (Fig. 8).

4.2.2. Sedimentary petrography

4.2.2.1. Lower Bach Ho member. The lithological components in the lower Bach Ho include mostly sandstone and claystone, with smaller siltstone and minor tuff rocks. Sandstones are mainly feldspathic greywackes, lithic arkoses, and arkoses. The texture characteristics and mineral composition of the rock are shown in Appendix B (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) (Fig. 9a). XRD result of the clay fraction in Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) indicates that the rock was probably in the early mesodiagenesis stage. In the SEM results, a mix of illite-smectite authigenic fills the pore spaces between the detrital grains, micropores, and macropores. The feldspar grains were partly dissolved to form secondary porosity (Fig. 9b). The Lower Bach Ho sediments were deposited in an environment with a changed flow from low to high energy due to the influence of tides depositing mainly in fluvial-delta

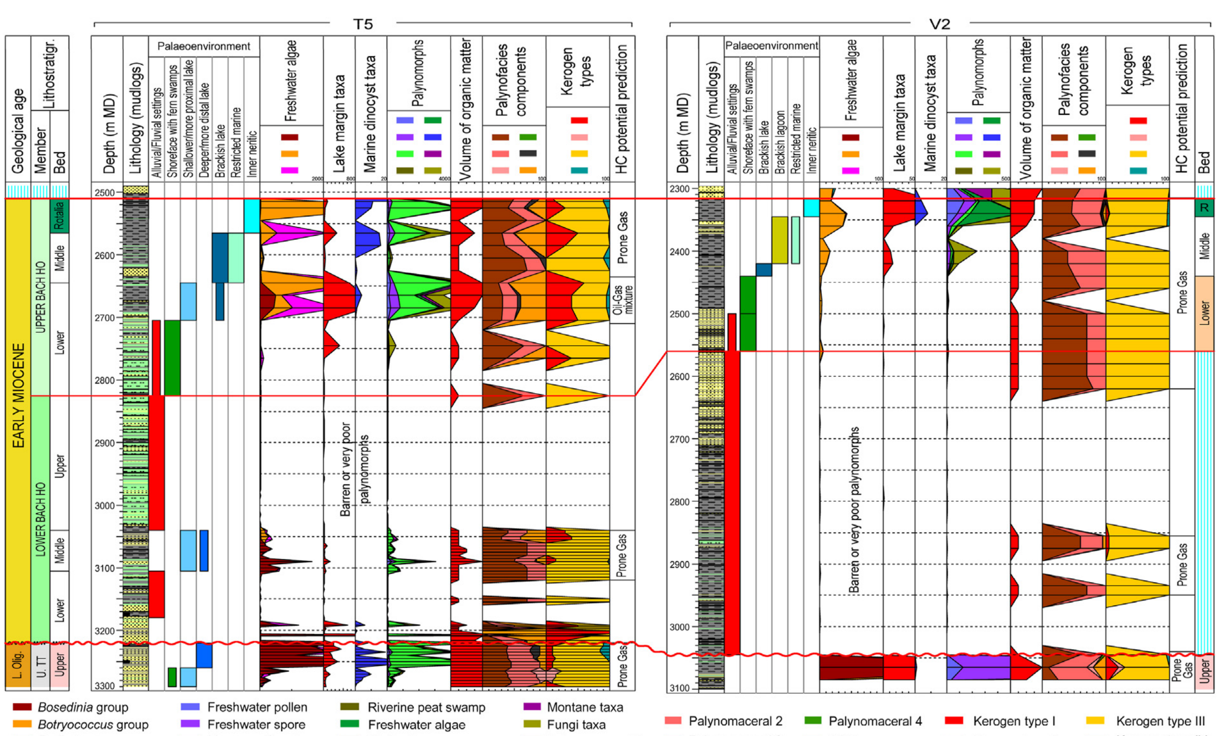

Fig. 8. Characteristics of the palynomorphs and palynofacies, hydrocarbon potentials prediction of the Bach Ho formation in the northeast (T5) and northwest (V2) of the study area.

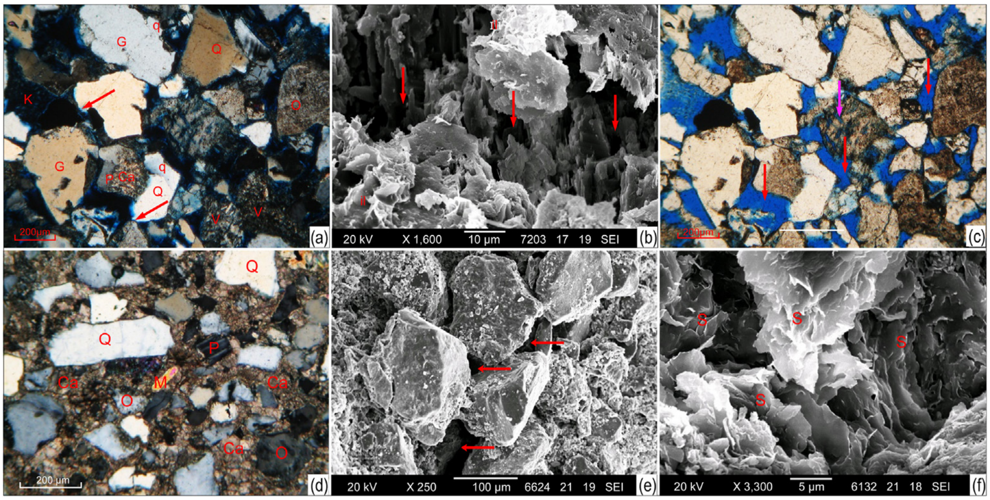

Fig. 9. Thin section and scanning electron microscopy photographs in the Bach Ho Formation. (a) Sandstone is weakly compacted with mostly point contact (red arrows) and is low cemented with kaolinite, quartz overgrowth (q), and some calcite minerals; (b) The feldspar grains are partly dissolved to form a secondary porosity (red arrows); (c) The sandstone is immaculate with good porosity consisting of primary intergranular porosity (red arrows) and partly enhanced by feldspar mineral dissolution (pink arrows); (d) The sandstone is tight and has no porosity due to poikilotopic calcite minerals, which fill all pore spaces; (e) Overview of sample surface displays the remaining intergranular pore (red arrows); (f) Smectite clays (S) occur in the form of thin flaky to slightly crenulated morphology, and they filled up intergranular pores.

environments. The reservoir rock quality is unevenly distributed and influenced by detrital matrix materials and secondary minerals, sometimes poikilotopic calcite (Figs. 9c and 10).

4.2.2.2. Upper Bach Ho member. The petrographic composition includes sandstone interspersed with claystone and siltstone. Sandstone was classified as main arkose, lithic arkose, or little feldspathic greywacke. The texture and mineral characteristics are shown in Appendix B (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) (Fig. 9d). The XRD analysis result for the clay fraction in Appendix C (https://ejp.researchcommons.org/cgi/viewcontent.cgi?filename=0&article=1034&context=journal&type=additional&preview_mode=1) indicates an early diagenetic stage (eodiagenesis) of the rocks. The sandstones were clean and fine-grained, indicating a lacustrine environment extending into a shallow marine environment under low-to medium-energy conditions. The matrix clay and secondary minerals are the main factors affecting the permeability and porosity of the formation; therefore, the reservoir rock quality in the Upper Bach Ho is not good in the study area (Fig. 10).

The highlight of this study is the recording of a marker sporomorph assemblage that was not younger than the Oligocene in the section that was classified as the lowest part of the Miocene in the

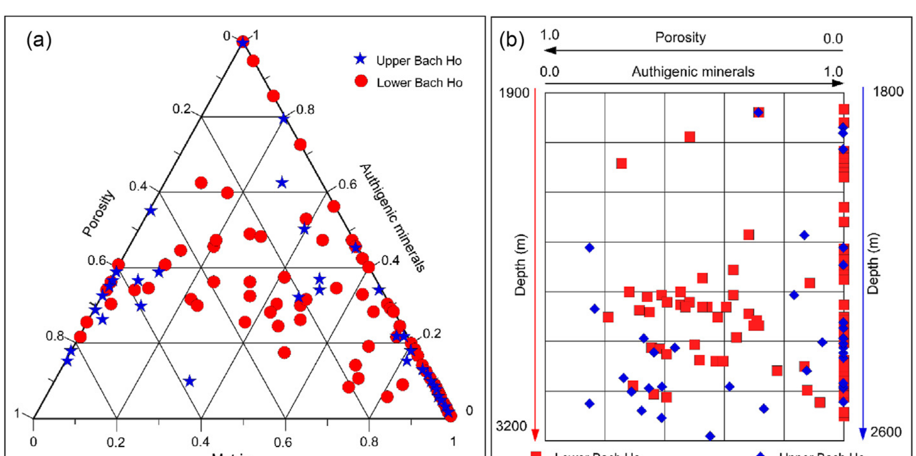

Fig. 10. (a) Relationship of matrix clay and authigenic mineral with the porosity of the Bach Ho Formation; (b) Relationship between authigenic mineral and the porosity of the Bach Ho Formation.

previous studies. Therefore, in this study, the authors propose to arrange these sediments in the highest section of the Tra Tan formation, corresponding to the Late Oligocene. This is a finding of stratigraphy using palaeontological methods.

5. Conclusions

This study provides the stratigraphic characteristics and reservoir quality of clastic sedimentary rocks of the Bach Ho and Tra Tan formations to support input data for the construction of geological models in the exploration and production stages in the oil and gas industry.

The sediment of the Tra Tan formation was divided into two members and was characterized by freshwater algae assemblages. The volume of organic matter was good and its component consisted of AOM, PM 1, and PM 2. The sediment was deposited in a freshwater lacustrine environment under low-to-high-energy conditions. The porosity was strongly influenced by the secondary and matrix materials and was not good in the Lower Tra Tan and moderate to good in the Upper Tra Tan. The geological boundary between the Miocene and Oligocene was corrected using palaeontological evidence.

The sediments of the Bach Ho Formation were divided into two parts with significant differences in their biostratigraphic characteristics. The lower part was poor or rare in palynomorphs and organic matter. It was deposited in the fluvial environment under high-energy conditions. This section had no potential for hydrocarbon generation; however, the reservoir rock quality was assessed as good. The Upper Bach Ho Member contained an abundance of palynomorphs from a freshwater lake to a shallow marine environment and was characterized by fossil zones with high stratigraphic correlation values. The volume of organic matter was medium to good and had the potential for hydrocarbon generation. The reservoir rock quality ranged from poor to moderate.

Ethics information

We commit that all research results and data received from analyzes and experiments on sample data collected by us. All samples used in this study were authorized by the organizations that managed and stored the samples. All references are fully and clearly cited. All authors participated in the research process and contributed to the manuscript.

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Author contributions

Conceptualization, Mai Hoang Dam, Tran Van Xuan, and Nguyen Thi Tham; data curation, Mai Hoang Dam, Nguyen Thi Tham and Bui Thi Ngoc Phuong; project administration, Mai Hoang Dam and Tran Van Xuan; formal analysis, Nguyen Tan Trieu, Vu Thi Tuyen, Pham Thi Duyen, and Nguyen Thanh Tuyen; investigation, Nguyen Xuan Kha, Dinh Viet Cuong, Nguyen Tuan, and Truong Quoc Thanh; writing-original draft, Mai Hoang Dam, Nguyen Tan Trieu, and Vu Thi Tuyen; writing-review & editing, Mai Hoang Dam, Tran Van Xuan, Nguyen Thi Tham, and Bui Thi Ngoc Phuong. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

There are no conflicts of interest.

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