Chapter

Petrological and Biostratigraphic Characteristics of Pre-Cenozoic Carbonate Rocks in the Northern Song Hong Basin, Vietnam

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Abstract

Pre-Cenozoic carbonate rocks in the northern Song Hong basin, Vietnam that are being considered and studied by oil companies in exploration and exploitation. The hydrocarbon accumulations in these rocks have been discovered and have significantly commercial reserves, in which the porosity plays an important role in estimating the capacity of hydrocarbon. The carbonate rocks are composed mainly of crystalline limestone, packstone, wackestone and mudstone, which have been experienced dolomitization, compaction and dissolution. The main carbonate pore systems include fracture, vuggy and intercrystalline porosity. The predominance of larger benthic foraminiferal assemblages indicates that the carbonate sediments were formed during the late Paleozoic (Carboniferous-Permian) and were deposited in shallow marine environment. Furthermore, the obtained petrological and biostratigraphic characteristics are well-correlated with the carbonate formations exposed in adjacent Cat Ba island area. The results of this study are either used in petroleum exploration or used in a local stratigraphic correlation in northern Vietnam.

Keywords: stratigraphy, lithology, pore types, foraminifera, hydrocarbon, reservoir model

1. Introduction

PetroVietnam recently discovered a hydrocarbon flow in the Pre-Cenozoic carbonate rocks of the northern Song Hong basin, Vietnam northern continental shelf, which has since become a potential object in oil and gas exploration operations and has attracted the interest of petroleum companies. As the Song Hong basin where penetrated by the petroleum exploration wells show that the basement rock formations are mainly sedimentary rocks which were deposited in shallow marine environment. They consist of strongly altered carbonate rocks with age varying from Permian to Early Carboniferous and their thickness reach over 500 m. The above covering of the basement rocks is the Cenozoic sediments and its petroleum systems have been considered within the framework of Cenozoic stratigraphy, this finding has suggested a new approach for managing the petroleum systems of the basin. Therefore, this area has been extensively investigated by PetroVietnam and foreign petroleum companies, and detailed studies have been conducted on the litho-sedimentological characteristics of the carbonate rocks [1–4]; the characteristics of the Mesozoic carbonate

reservoir [5]; determining the geological age and building a geological prediction model for the Pre-Cenozoic carbonate basement [6]; and other projects [7, 8] in the northern Song Hong basin. However, geological data for this area is limited, therefore, PetroVietnam has indirectly conducted many studies using field models that focus on the outcrops in areas adjacent to the northern Song Hong basin. One of the problems currently under discussion is the petrological characteristics and ages of the carbonate formations of the carbonate rocks and their relationship in the northern Song Hong basin and the adjacent areas. Many field studies have been conducted to evaluate the petrology, stratigraphy, and tectonic characteristics of the Cat Ba, Co To, and Bach Long Vi islands and their adjacent areas, including Hai Phong, Ha Long Bay, and Quang Ninh. The results of these studies show that the ages of the carbonate formations of the study area in the northern Song Hong basin are similar to those of several islands in the Vietnam northern shelf, according to the characteristics of foraminiferal assemblages. Therefore, this study aims to characterize the petrology and stratigraphy of the carbonate formations in the northern Song Hong basin and their correlation with those of adjacent island. Three wells at a depth of over 3500 m with a carbonate rocks thickness of approximately 500 m were studied in the northern Song Hong basin. This study is very important for providing petrological characteristic and evidence regarding foraminiferal fossils to determine the stratigraphic relationship between wells and adjacent areas. It might also be applied for stratigraphic correlation and comparison of reservoir models in the wells.

2. Geological settings

The study area is located at northern Vietnam on the South china plate (**Figure 1**). In the Late Paleozoic, the South China plate collided with the Indochina plate and formed a broad northwest-southeast mobile belt, which included the Ailaoshan, Song Ma, and Dian-Qiong sutures that represent the complex boundary zone between the Indochina and South China plates in northern Vietnam, and the southeastern part of the South China plate [9]. The Song Ma suture zone is composed of large amount of serpentinite, altered gabbro, and chromitite. The serpentinite may serve as a remnant of the Paleo-Tethys oceanic lithosphere [10]. According to Metcalfe [11], large-scale folding, thrust, and nappe formation in the Early-Middle Carboniferous, blanketing Middle Carboniferous strata, and plant remains suggest that this suture was originated in the Early Carboniferous.

The northern Song Hong basin is composed of Pre-Cenozoic rocks, including carbonate, clastic, and metamorphic rocks, which are overlain by Cenozoic rocks [12]. Carbonates are the major rocks, while the other rocks are present to a lesser extent. The carbonate rocks consist of about (500 m thick) of Paleozoic successions originating during Devonian and Permian [8, 13–21]. Limestones are classified dolostone and crystalline limestone. The dolostones were probably originally mud-supported limestones that have been partially to completely replaced by variably finely to coarsely crystalline, anhedral to subhedral (xenotopic to hypidotopic), rhombic dolomites and are classified probably as crystalline dolostones. Crystalline limestone, in which lime mud matrix has mostly recrystallized to microspar/pseudospar. Locally, limestone has been fractured. There also appear some dolomite conglomerates, which are predominantly made up of gravel-sized dolomite grains and dolomite cement.

The northern part of this area is in the Quang Ninh zone, the southern part is located in the western part of Bac Bo (Tonkin) Gulf [22], and the entire study area is in the northern Song Ma suture zone. In which, the Quang Ninh zone is studied quite in detail on petrography and paleontology in the sections on Cat Ba island. The exposed lithology on Cat Ba island is dominated by carbonate rocks that have been

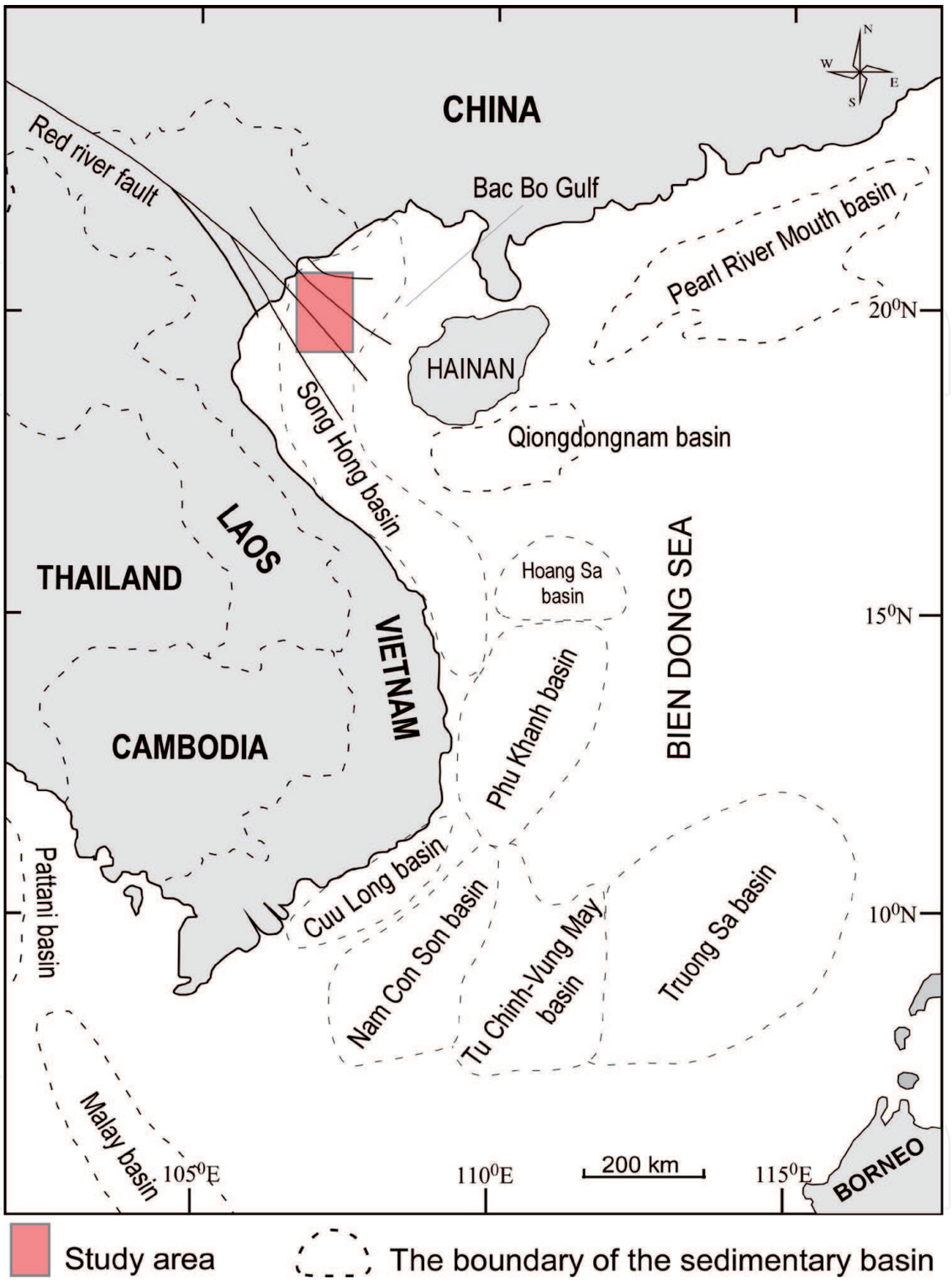

Figure 1.
Map of the sedimentary basins of Vietnam continental shelf and adjacent areas, and the location of study area [4].

described and updated by [13, 20, 23, 24], and consists of the Trang Kenh (D_2-D_3 *tk*), Pho Han (D_3-C_1 *ph*), and Bac Son (C-P *bs*) formations (**Figure 2**).

3. Materials and methods

The current study was performed using petrographic microscopy, scanning electronic microscopy (SEM) and X-ray diffraction (XRD) analysis. 81 thin-sectioned

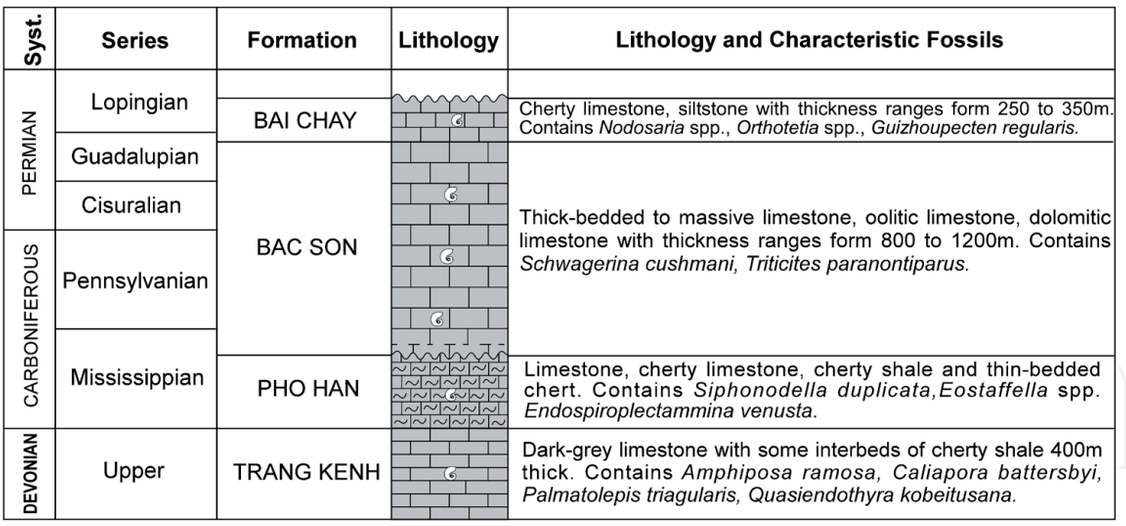

Figure 2.
The late Paleozoic stratigraphy column of the Northeast Vietnam (Bac Bo Gulf) [25].

from carbonate units were prepared and stained by ARS (Alizarine Red Solution) to distinguish calcite and dolomite using Dickson's method [26]. Thin sections were studied under polarized microscopy to analyze petrography. The determination of visible porosity was performed by modal analysis, which involved counting 300 points per thin section [27, 28]. The carbonate rock was classified based on Dunham's classification [29] and its modification by Embry and Klovan [30]. 218 additional oriented thin sections are used to identify foraminifera (genus or species names). If the foraminifera were found to be relatively large upon separation from the carbonate debris, they were fixed onto the glass slide and then polished until all chambers or internal structures could be observed.

31 samples of dolostone and limestone were examined using a JEOL Scanning electronic microscope (SEM) in order to identify and assess the morphology, type of authigenic minerals and their relationship to framework grains and pore network.

93 samples of dolostone and limestone were examined using D8-Advance automatic system that carried out X-ray diffraction (XRD) analysis for determining the mineralogical composition based on amount in term of Semi-Quantitative. All of them were performed at Vietnam Petroleum Institute (VPI) in Vietnam.

4. Results and discussions

4.1 Petrological and stratigraphic characteristics of carbonate rocks in the early Carboniferous

The Early Carboniferous carbonate rocks has sporadically been interbedded dolostone, limestones and dolomitic limestones and a small amount of limestone alternating clamps, with a thickness of approximately 400 m to belong to the Pho Han (D_3-C_1 *ph*) formation. Dolostones consist of euhedral and subhedral rhombic dolomite crystals with planar-euhedral and planar-subhedral texture [31] (**Figure 3**). These rocks have severely been affected by compaction, which are manifested by stylolitization and fracturing. Foraminifera fossil could be not found due to dolomitization. Limestone is classified mainly of lime-mudstone and minor amount of packstone. The lime-mudstones are composed of micrite and microspar calcite. The skeletal grains consist of mainly well-preserved benthic foraminifera and bioclasts.

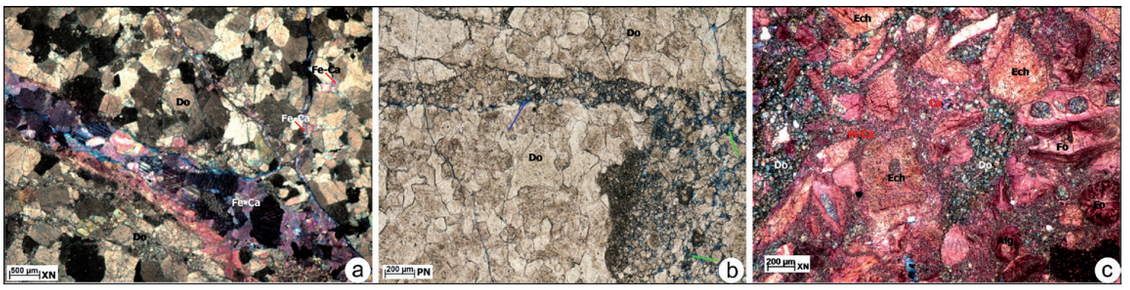

Figure 3.
a. Dolostone is composed of mainly dolomite with euhedral and subhedral rhombus, made up of planar-euhedral and planar-subhedral. Ferroan calcite (Fe-Ca) is remained in dolostone and fill in the fractures; b. Dolostone is composed of mostly subhedral rhombic dolomite (Do). The visible porosity appears in between dolomite crystals; c. Packstone interbeds in dolostone at the 3750 m and 3900 m depth. Packstone is consisted of fossils including echinoderm (Ech), foraminifera (Fo), algae (Alg), bio-fragments and non-ferrous, micrite calcite (stained in pink color). The fossils contacts together and micrite dolomite (Do) appears either inner fossils or on matrix.

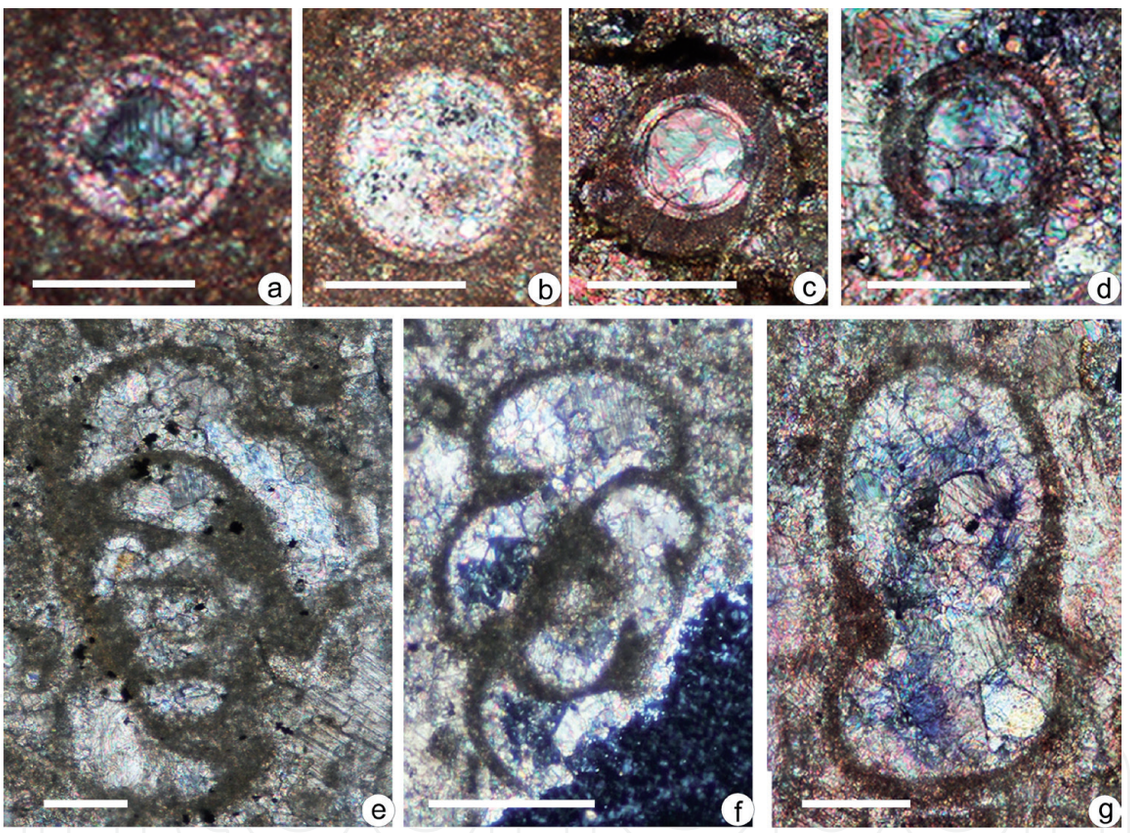

Figure 4.
The characteristic foraminiferal assemblage of the lower middle Tournaisian in the Song Hong basin; a–d. CALCISPHAERIDAE (Williamson, 1880); e. Septabrunsiina kazakhstanica *(Reitlinger, 1961); f.* Septabrunsiina *sp. (Lipina, 1955); g.* Tournayella (?) *sp. (Dain, 1953). Scale bar is 100 μm.*

Two foraminiferal assemblages were identified in the studied interval which is from a depth of 3500–4000 m. The lower part contains unilocular foraminifera, while the upper part consists of Tournayellids. The unilocular foraminifera group characterized by abundant *Calcisphaera* and *Parathurammina*. This assemblage is considered to represent the upper region of the unilocular intermittent zone [21] and indicates that the carbonate formation was originated during the latest Early Tournaisian (**Figure 4a–d**). A fossil assemblage of Tournayellidae, include *Tournayella*, *Septabrunsiina kazakhtanica*, and *Septabrunsiina* sp. This assemblage was characterized by the clear evolution of septa between the chambers, which are affiliated with the lowermost part of the *Chernyshinella-Palaeospiroplectammina*

zone in the Cat Co and Gia Luan sections. This suggests that this assemblage was formed during Early to Mid-Tournaisian (**Figure 4e–g**).

Generally, the carbonate of this formation has been strongly replaced by fossil remains that are found scattered in the limestone layers and the visible porosity is noted as retained fracture pores and intercrystalline pores.

4.2 Petrological and stratigraphic characteristics of carbonate rocks in the late Carboniferous

The Late Carboniferous carbonate rocks appear at the depth roughly 3400–4150 m and is consisted of limestones, dolostones and crystalline limestones. At the upper part, the carbonate rocks are interbedded with basalt tuffs and with silic dikes/veins at the lower.

Almost all carbonate rocks are mud-supported type. Limestones are classified mostly as dolomitic-calcitic mudstone, wackestone and packstone. The allochems mainly consist of Foraminifera (fusuline), algae, coral and echinoderm (**Figure 5**), while the groundmass are micrite and microspar. The Lime mud matrix (micrite) has been partly to totally replaced by finely to coarsely crystalline, anhedral to subhedral dolomites (non-ferroan dolomite) and sparry calcite with calcite crystals ranging 10–15 μm diameter (as ferroan calcite, up to 35% and non-ferroan calcite, up to 70%). The carbonates have more or less been replaced by quartz. They have also suffered compaction in the form of fractures; however, all fractures have been filled by sparry calcite, sparry ferroan calcite and silica cement (**Figure 6c** and **d**).

Dolomitic-calcitic limestone that is lime mud matrix recrystallized into microcalcites and replaced by dolomite, was probably originally mud-supported limestone that has been strongly recrystallized to microspar carbonate crystals. The rock consists of abundant carbonate fragments with trace skeletal particles as foraminifera, echinoderm that floating on micrite carbonate matrix. A small amount of very fine to fine sand-sized secondary quartz grains are present. The rock has been undergone the compaction and dissolution in post-deposition. As results, the fractures crossed throughout the carbonate rocks forming stylolite texture and fractures; however, fractures are occluded by calcite and ferroan calcite; minor fracture pores are preserved.

Carbonate allochems consist of algae, foraminifera, and echinoderm. All fossil skeletons have been undergone micritization, however, their cellular structures are locally preserved. Commonly, allochems and micritic carbonate have strongly been recrystallized to with minor amount of ferroan calcite on lime mud matrix.

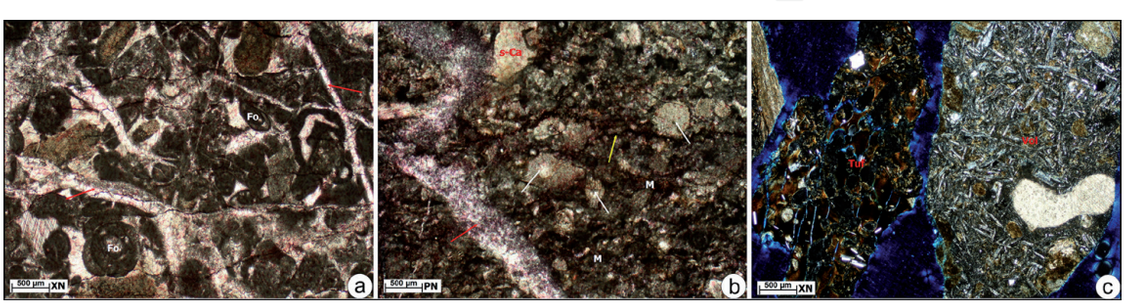

Figure 5.
Thin section photography of carbonate rock in the Song Hong basin. a, b. both wackestone and packstone consist of foraminifera (Fusuline, Fo) and crinoids (white arrows), which are floating in the lime mud matrix. All crinoids have strongly been undergone calcitization. The lime mud matrix has locally been replaced by – Calcite minerals. Compaction represented by fractures and stylolities, which are filled up by ferroan calcite cements; c. volcanic dikes (Vol) and basalt tuffs (Tuf) cross-cutting both grains and matric.

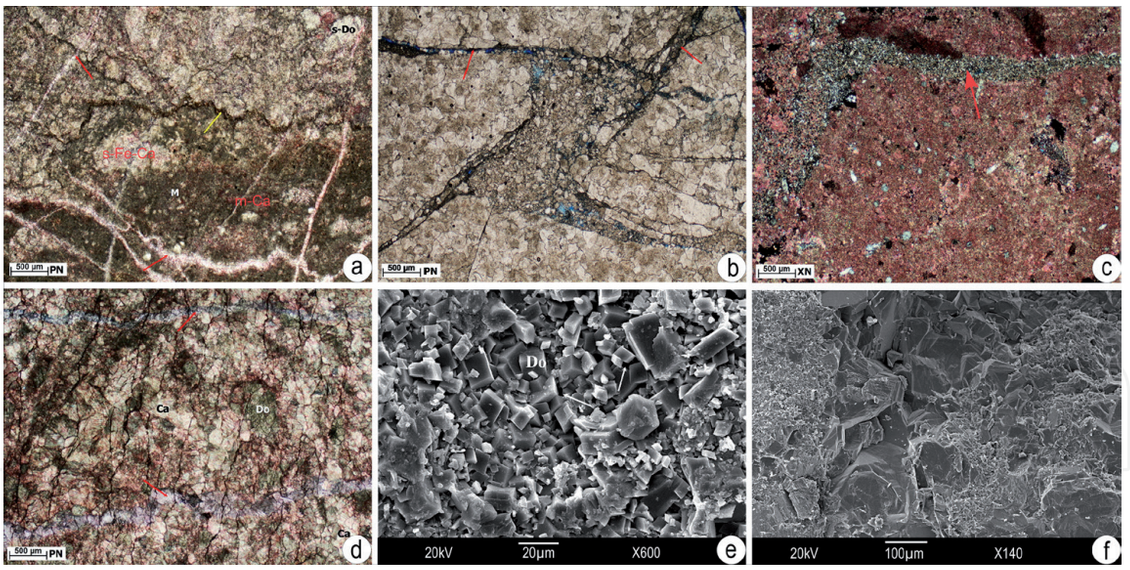

Figure 6.
Thin section and SEM photography of carbonates in the Song Hong basin. a, b. the carbonate rocks have strongly been undergone tectonic activity, resulting in crushed fracturing (red arrows) and complex stylolization (yellow arrow); c. the fractures have been filled up by calcite, chert and ferroan calcite (red arrow); d. the fractures have been filled up chert as seen authigenic quartz and chalcedony then calcite grows (Ca) in remained pores; e. the development of rhombic dolomite crystals, creating many of intercrystalline pores; f. limestone has been completely crystallized into variably coarsely crystalline, anhedral to subhedral calcite and locally replaced with finely rhombic crystallines of dolomite. The sample has been fractured and fractures have been filled up by calcite minerals (along the middle).

The rock has been fractured and almost all fractures have been filled with calcite or ferroan calcite. The size of fractures changes from 0.02–0.4 mm in width.

Crystalline limestones are mainly consist of lime mud that is recrystallized into calcite. Minor allochems are present as echinoderm. The rock have been undergone compaction and dissolution that formed stylolite and fractures.

Dolostone has mud-supported limestone that partially to completely replaced by finely to coarsely crystalline, anhedral to subhedral (xenotopic to hypidotopic), rhombic dolomites. The size of dolomite crystals commonly range from 0.15–0.4 mm, and exhibit equigranular texture. Dolostone has been compacted and formed stylolite and fracture system complication (**Figure 6a** and **b**). It indicates that this rock has been affected by compaction during burial diagenesis. Fractures have been occluded by dolomite crystals.

The result of Scanning Electric Microscope (SEM) analysis show that displays the morphology coarsely crystalline, anhedral to subhedral calcite and locally replaced with finely rhombic crystallines of dolomite and rhombic dolomite crystals, creating many of intercrystalline pores (**Figure 5e** and **f**). The XRD result for whole-rock shows rock-forming minerals of carbonate basement, in which calcite and dolomite are homogeneously present in high levels. Quartz is also sporadically present with high amount. K-feldspar and plagioclase are nearly totally disappeared.

Diagenetic processes, such as micritization, may be contemporaneous with diagenetic process such as cementation. Diagenesis has included micritization of bioclasts and infiltration of micrite calcite into the foraminifera chambers; after that recrystallisation of micrite into microspar and pseudospar sizes; fracturing and non-selective dissolution of calcite, followed by precipitation of blocky calcite cement and locally formed of xenotopic to hypidiotopic dolomite.

In general, the visible porosity of carbonate rocks is mostly formed by dolomitization, dissolution and fracture. It is present as intercrystalline pores, which is formed from the dolomitization; whereas, fracture pores have been created by tectonic activity; vuggy pores that have been formed by the shrinkage of matrix and dissolution of

skeletal debris; with minor moldic pores. Carbonate has more or less been fractured; however, almost all fractures have been filled up with silic and calcite due to hydrothermal activity. Therefore, the reservoir quality of the rock has been restricted.

The petrographic analysis result indicated that limestones are classified mostly as crystalline dolomite, dolomitic-calcitic mudstone, wackestone and packstone. These limestones are predominantly made up of carbonate allochems as Foraminifera (as Fusuline), Algae, Coral and Echinoderm, which have been stylolitised and fractured due to tectonic activity. The rocks have also been strongly altered with silic, which resulting from volcanic activity in post-deposition. It is vital for pointing to the depositional settings that were frequently in low to moderate-energy flow and affected by sea-level fluctuation and deposited in a reef-continental shelf shallow marine environment. This reef has more or less been affected by tectonic activity and volcanic activity, in which carbonate has been fractured, stylolitised and altered with silic minerals.

Two foraminiferal assemblages were identified in the studied interval which characterizes the Serpukhovian-Early Bashkirian and Late Moscovian age. The *Millerella-Eostaffella* zone was observed in the ~150 m thick limestone formations of the lower section of the basement. This zone was characterized by the abundant Pseudostaffellinae including: *Eostaffella, Neostaffella, Mediocris,* and *Pseudoendothyra,* common *Palaeotextularia,* and sudden disappearance of Endothyrinae at the

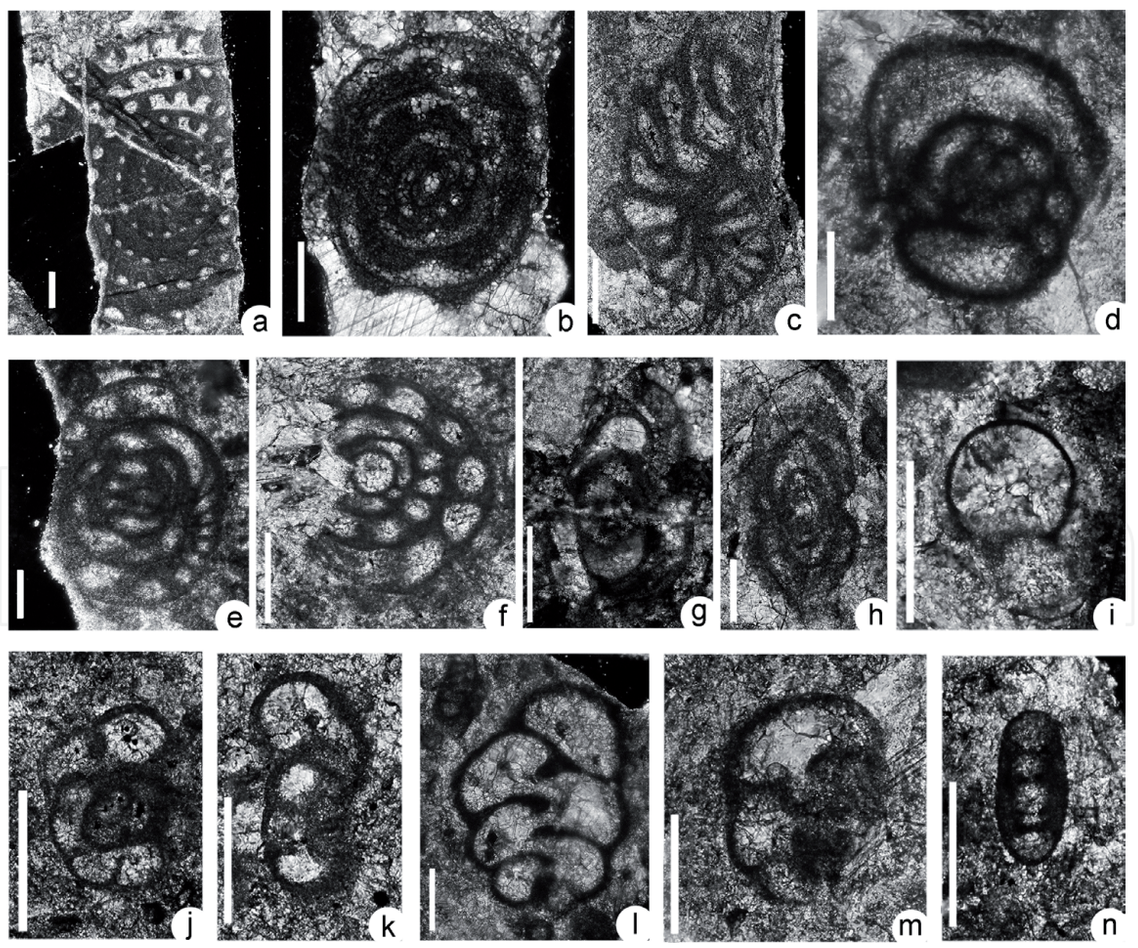

Figure 7.
The characteristic foraminiferal assemblage of the Serpukhovian-Moscovian in the Song Hong basin. a. Profusulinella *sp. (Rauzer-Chernousova and Belyaev, 1936); b.* Neostaffella *sp. (Miklukho-Maklay, 1959); c. Fusulinid fragment; d.* Grovesella *sp. (Morelet, 1969); e.* Schubertella *sp. (staff and Wedekind, 1910); f.* Fusulinella *sp. (Möller, 1877); g, h.* Pseudoendothyra *spp. (Mikhaylov, 1939); i.* Eotuberitina *sp. (Miklukho-Maklay, 1965); j, k. ENDOTHYRINAE (Brady, 1884); l.* Palaeotextularia *sp. (Simakov, 1992); m.* Globivalvulina *sp. (Simakov, 1992);* n. Mediocris *sp. (Rozovskaya, 1961). Scale bar is 100 μm.*

end of the Serpukhovian [32]. The upper region of this zone contained the first *Profusulinella* and Ozawainellidae, which are indicative of the upper Bashkirian [14, 21] (**Figure 7**). The foraminiferal assemblage of this zone is similar to that in the uppermost Serpukhovian to upper Bashkirian in the Gia Luan section.

The *Fusulinella-Fusulina* zone was found in the ~100 m thick limestone in the middle section of the basement. It was identified by the abundances of *Profusulinella, Fusulina, Schubertella*, Ozawainellidae, *Globivalvulina*, and *Eotuberitina* (**Figure 7**). This zone is indicative of the upper Moscovian. In addition, calcareous algae groups are abundant in this zone, with *Beresella* appearing as the most predominant genus. This genus first appeared at the end of the early Carboniferous (Serpukhovian) and was the most abundant in the first half of the late Carboniferous, from the Bashkirian to the Moscovian [33, 34].

4.3 Petrographical and stratigraphic characteristics of carbonate rock in the middle-late Permian

In this studied section, the Early Carboniferous carbonate rocks appear at the depth roughly 3505–4050 m and is consisted of wackestone, packstone and mudstone to belong to Bac Son (C-P *bs*) formation. At the lower part, the carbonate rock is verified mainly as packstone with grain supported and contains many foraminiferal fossils. The majority composition minerals of limestone is non-ferroan calcite (stained in pink), locally ferroan calcite (stained in mauve), and ferroan dolomite. The limestones contain carbonate allochems as benthic foraminifera, echinoderm, coral, algae, bryozoa, brachiopod. The limestones are highly fractured and stylolitised owing to tectonic activity, squeezing, diagenesis, that filled up by ferroan calcite, dolomite (**Figure 8**).

After silicate (chalcedony) depositional process, the crystalline minerals filled up the fractures which is a dyke intruding into the limestone and nodules fill in the fractures. The visible porosity of carbonate rock is created by the dissolution of vuggy pores and fractured pores that locally preserved. Carbonate basement rock is classified as after Dunham's classification [29], analyzed limestones are verified as wackestone, packstone and mudstone types.

Packstone contains a fair level of fossils such as foraminifera, algae, echinoderm, coral, bryozoa, brachiopod and other bio-fragments that contains more than 10% in total rock composition. Carbonate allochems and bio-fragments contact together and cemented by lime mud that is crystallized to microspar calcite (4–10 μm), pseudospar calcite (10–50 μm) and locally dolomitised. All fossil skeletons have been completely altered by calcite, their cellular structures are also altered by calcite

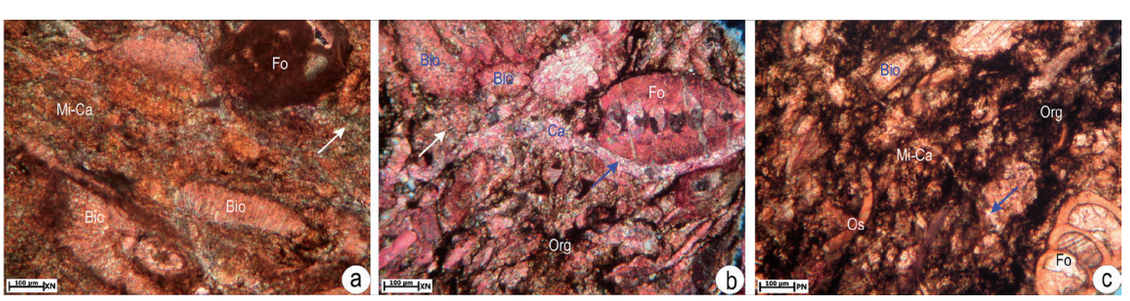

Figure 8.
Thin section photography of Permian carbonate in the Song Hong basin. The main components are non-ferroan micrite calcite (Mi-Ca, stained in pink) intermixing with minor amount of organic matter (Org), locally replaced by dolomite (white arrows) and quartz. The rock contains bio-fragments such as foraminifera (Fo), ostracod (Os) and unidentified bio-fragments (Bio). The rock has been squeezed and created fractures (blue arrows), filled up by calcite (Ca).

and locally well preserved. Limestone has been fractured but the fracture pores are occluded by calcite (stained in pink) and ferroan calcite (stained in mauve).

Wackestone contains smaller amount of fossils such as foraminifera, ostracods, algae other bio-fragments that contains about 10% in total rock composition. Bio-fragments are floating on lime mud matrix that micrite texture and locally altered into dolomite and replaced by silicite. All fossil skeletons and their cellular structure are altered and filled up by calcite. Limestone has been fractured, stylolite texture, filled up by non-ferroan calcite.

Mudstone contains dominantly lime mud, micrite texture that is crystallized into microspar calcite and micrite calcite (<4 μm). Carbonate allochems as foraminifera, ostracods and unidentified bio-fragments that contain less than 10% in total rock composition. Carbonate allochems are floating on lime mud matrix, and locally altered into dolomite and replaced by silicate.

Dolostone has been formed from packstone, wackestone that dolomitised in the alteration post-depositional process and interbedded in packstone and wackestone. Dolostone have planar-subhedral texture and carbonate allochems in dolostone have been dolomitised.

The result of (SEM) analysis reveals the crystalline morphology of micrite calcite (Ca), size <4 μm and rhombic dolomite (Do) with euhedral with size >50 μm (**Figure 9e** and **f**). Together with the whole rock XRD results indicated that the most predominant volume is carbonate minerals in which mainly calcite and less than as dolomite, rarely siderite. Minor amount of quartz, feldspar minerals are also found at this interval.

The petrographic analysis result in this study shows limestone experienced the alteration post depositional process such as the crystalline of lime mud altered into calcite, dolomitised. The squeezing and dissolution process created fractures and stylolite textures, locally fractures filled up by calcite, dolomite and silicate.

Lime mud has been crystallized and altered into calcite; Whereas, lime mud in bio-fragments crystalline altered into micrite calcite and sparry calcite that surrounded bio-fragments and created poikilotopic texture.

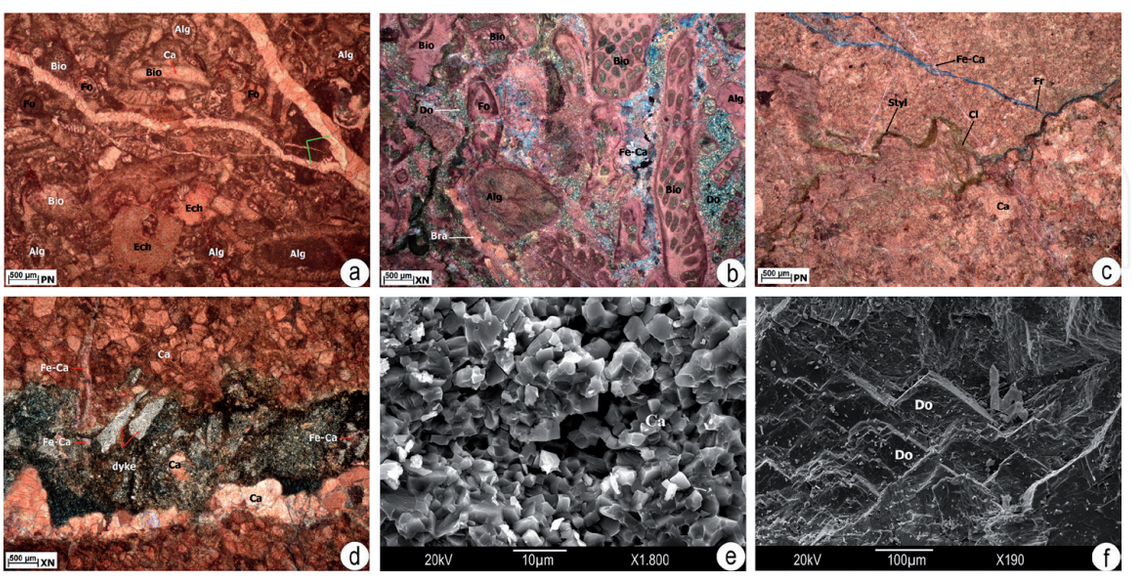

Figure 9.
Thin section and SEM photography of Permian carbonates in the Song Hong basin. a-b. The main composition of the rock is non-ferroan calcite (Ca, stained in pink), locally replaced by dolomite (Do). Carbonate allochems include foraminifera (Fo), echinoderm (Ech), algae (Alg) and unidentified bioclasts (Bio); c-d. The rock has been squeezed and created fractures (arrows) and stylolite texture (Styl), filled up by clay minerals (Cl), ferroan calcite (Fe-Ca) and silica dyke; e-f. Calcite minerals (Ca) are replaced by dolomite (Do) with subhedral shape.

Dolomitised shows that micrite calcite has partly been altered by dolomite and locally filled up fractures. Dolomite crystals are more anhedral formed after that, in buried stage.

Fracture and stylolite have been formed by tectonic activity and they were filled up by calcite, dolomite.

Generally, the visible porosity is mainly fractured pores, vuggy and moldic pores intergranular pores between dolomite crystals. Because of the impaction hydrothermal activity, vuggy, fracture that infilled by silica dyke and nodule into limestone and restricted the reservoir quality of the rock, so the fracture pores are estimated in poor.

Based on the petrographic analysis result, the presence of fossils such as especially foraminifera group in mudstone and wackestone that contain lime mud, some bio-fragments and dominantly deposited in low energy marine, steady current. Packstone contains abundant carbonate allochems that have been deposited in marine environment with the changes of energy current from low to high and on the contrary.

The fossil skeletons were mainly replaced by calcite cement and dolomite and the inside of the chambers were also dolomitised but the structure of the skeleton is still very well preserved. The fossil assemblages found to characterize Late Paleozoic (Permian) is mainly distributed in northeast Vietnam and adjacent areas [21, 35]. The typical representatives include genera: *Nodosinelloides, Nodosaria, Geinitzina, Codonofusiella, Pachyphloia, Rectoglandulina, Palaeotextularia, Reichelina, Cribrogenerina* and popularity of fossil fragments of the Fusulinacae superfamily were dominant in samples, which exhibit strong folding septa and very clear keriotheca that are typical of the Schwagerinidae family (**Figure 10**), and are mainly distributed from the Kasimovian (Late Carboniferous) to the Capitanian (Middle Permian) [36–38]. In addition, the presence of the *Geinitzina, Pachyphloia, Nodosinelloides*, and *Cribrogenerina* genera in this well was also characteristic of the Permian [39, 40]. Moreover, algal groups mainly consisting of Konickopora were abundant. The first representative Konickopora in southern China were observed in formations from the Serpukhovian, and they became abundant in the Permian. The abovementioned foraminiferal assemblages suggest that this carbonate formation originated during the Capitanian-Wuchiapingian.

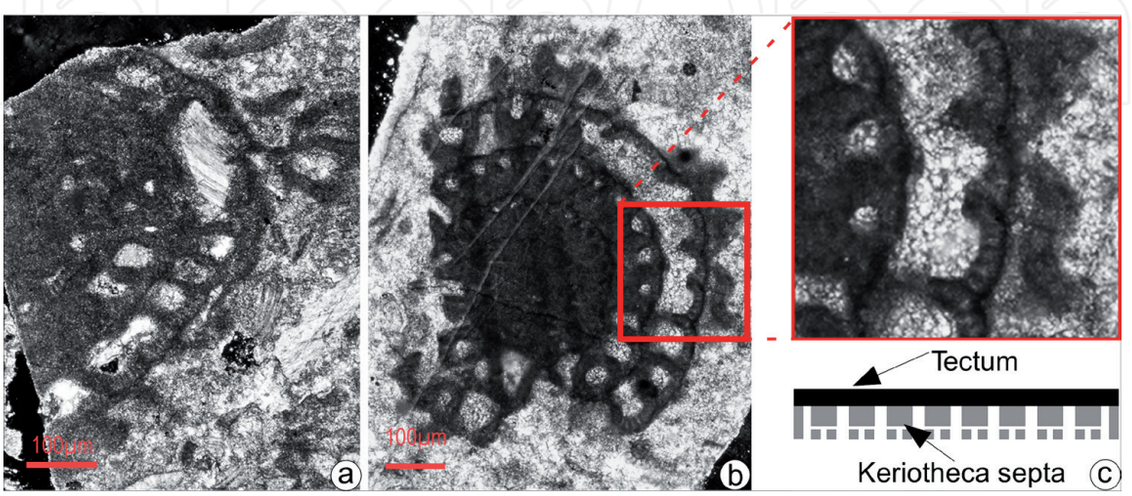

Figure 10.
a, b. Characteristics of the keriotheca septa of the Schwagerinidae family found in the study well; c. detailed structure of the keriotheca septa.

According to previous studies [21, 35] which were recorded the distribution of foraminifera assemblages in many areas on the Vietnamese continent and adjacent areas (**Figure 11**).

Genus *Globivalvulina* Schubert, 1921 was distributed stratigraphy from Serpukhovian to the latest Permian [41]. Genus *Reichelina* Erk, 1942 was identified in the range from Wuchiapingian to Changhsingian in South China [41]. In northern Vietnam, the distribution stratigraphy of *Reichelina* in Late Permian was found mainly in the Northeast to belong to Bac Son (Wuchiapingian) and Dong Dang (Changhsingian) Formation [21].

Genus *Pachyphloia* Lange, 1925 appeared first from Sakmarian and disappeared in the latest part of Permian in South China [41]. In Vietnam, *Pachyphloia* has been

Figure 11.
Characteristic foraminifera assemblage of the Permian in the Song Hong basin. a-c. Nodosinelloides *spp. (Mamet and Pinard, 1992), d-e.* Geinitzina *spp. (Spandel, 1901), f.* Protonodosaria *sp. (Gerke, 1959), g.* Geinitzina *sp. (Spandel, 1901), h-i.* Sichotenella *spp., j.* Globivalvulina *sp. (Schubert, 1921), k.* Protonodosaria *sp. (Gerke, 1959), l.* Pachyphloia *sp. (Lange, 1925), m.* Pachyphloia *sp. (Lange, 1925), n.* Pachyphloia *sp. (Lange, 1925), o.* Diplosphaerina *sp. (Derville, 1952), p.* Protonodosaria *sp. (Gerke, 1959), q.* Pachyphloia *sp. (Lange, 1925), r.* Cribrogenerina *sp. (Schubert, 1908), s.* Nodosaria *sp. (Lamarck, 1812), t.* Neodiscus *(?) sp. (Miklukho-Maklay, 1953), u.* Protonodosaria *sp. (Gerke, 1959). Scale bar is 100μm.*

commonly found from the Middle to Late Permian and widespread in the northeast area to belong to the Bac Son and Dong Dang Formations [21].

Genus *Schubertella* Staff and Wedekind, 1910 was commonly found in the northern Vietnam (Bac Kan, Quang Ninh, Thai Nguyen, Quang Binh) in the range from Late Carboniferous (Moscovian) to Permian to belonging to the Bac Son Formation [21]. Genus *Cribrogenerina* Schubert, 1908, distributed in Late Permian (Changhsingian) of the Dong Dang Formation, was found in Cao Bang, Lang Son [21]. Family Schwagerinidae Dunbar et Henbest, 1930 is characteristic to the Permian of the Bac Son Formation in the North and the South of the Ha Tien Formation [21].

An assemblage of *Nodosinelloides–Geinitzina* which was characteristic of the Early Permian was recorded in Iran [42]. *Codonofusiella–Reichelina* assemblage is abundant in the northeast to belonging to the Bac Son Formation (Wuchiapingian). Genus *Codonofusiella* Dunbar et Skinner, 1937 distributed in the Middle-Late Permian to belong to the Bac Son, Dong Dang, Ha Tien Formations.

5. Conclusions

The carbonate rocks in the study area were originated during Late Paleozoic and have been determined by the foraminiferal fossils which show stratigraphic distribution ranges from the Early Carboniferous (Tournaisian age) to the Late Permian (Capitanian-Changhsingian age). These assemblages reveal the stratigraphic relationship that exists between the carbonate formations in Cat Ba island and the basement rock in the northern Song Hong basin, and provides chronostratigraphic data that can be used in geological models used for hydrocarbon exploration. Most of the carbonate rocks in the Carboniferous period are major dolostone and minor crystalline limestone, wackstone and packsonte.

The carbonate rocks have undergone the post-depositional alteration. The rock fabric and rock composition have changed as lime mud changes micro and sparry calcite with larger size and calcite replaced dolomite which is different component. Dissolution of minerals in the chemical diagenesis leave pores. Additionally, calcite micro and sparry are replaced by silic materials as quartz. The carbonate rocks are highly fractured and compacted forming fractures and stylolites; however, the fractures are infilled by calcite and dolomite in the later diagenesis and the fractures are also blocked by silica materials owing to hydrothermal activity.

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Conflict of interest

All authors have participated in (1) conception and design, or analysis and interpretation of the data; (2) drafting the article or revising it critically for important intellectual content; and (3) approval of the final version.

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