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New insights into the Triassic sedimentary environment of the eastern parts of the Song Da and Sam Nua basins alongside the Indosinian Song Ma suture, Northern Vietnam

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Abstract

This study documents the sedimentology, structures, and foraminifer content of Triassic formations from the eastern part of the Truong Son Belt (Northern Vietnam). Sedimentary rocks in the eastern Song Da and Sam Nua basins occur on both sides of the Middle Triassic

Song Ma suture zone that separates the Indochina Block from the South China Block. The main outcomes of our study include detailed stratigraphic successions that we have established for the two basins. New foraminifer determinations indicate a Middle to Late Triassic age for the carbonate deposition. The depositional settings of the carbonate deposits and their deformation patterns support a southward "subduction" beneath the Indochina Block, ending with the collision with the South China Block during the Middle Triassic. Moreover, our new biostratigraphic dating of the stratigraphic successions can be used to compare the Triassic carbonate platforms from Northern Vietnam with other platforms elsewhere, including those that have already been well documented in Indonesia.

Keywords

Stratigraphy, Foraminifers, Sedimentology, Carbonate platforms, Indosinian orogeny, Northern Vietnam

1. Introduction

During the Triassic, extensive carbonate platforms developed in different basins in Southeast Asia (Khuc and Huyen, 1998; Payne et al., 2006; Galfetti et al., 2008; Lerhmann et al., 2015), including those in Northern Vietnam (Khuc and Huyen, 1998; Martini et al., 1998; Algeo et al., 2007; Son et al., 2007; Komatsu et al., 2010; Metcalfe, 2012). These platforms provide important information that can be used to document the global environmental evolution and biotic recovery after the end-Permian mass extinction (Algeo et al., 2007; Son et al., 2007, Komatsu et al., 2010; Metcalfe, 2012). However, the precise stratigraphic framework for the

Northern Vietnam Triassic carbonate platforms is still incompletely characterized (Shi and Shen, 1998; Martini et al., 1998; Tri and Khuc, 2011; Thanh and Khuc, 2012; Rossignol et al., 2016, 2018), making it difficult to make correlations and comparisons with other platforms of similar age worldwide and in Southeast Asia.

The Early and Middle Triassic carbonate platforms of Northern Vietnam developed in foreland basins associated with the onset and growing of the Indosinian orogen from the Early to the Late Triassic (Lepvrier et al., 2008; Vuong et al., 2013; Faure et al., 2014, 2016; Roger et al., 2014; Halpin et al., 2015; Rossignol et al., 2018). The studied areas concern the Song Da Basin, located to the southwest of the Indosinian orogen, and the Sam Nua Basin, bordering the orogen to the northeast. These basins are separated by the Song Ma Ophiolitic Suture Zone, which is located along the Song Ma Fault (Fig. 1). This suture zone corresponds to the boundary between two continental blocks (Ridd, 1971; Metcalfe, 1988, 2011; Lepvrier et al., 2008; Vuong et al., 2013; Faure et al., 2014, 2016, and references therein): the South China Block (SCB) to the north and the Indochina Block (IB) to the south (Fig. 1). The collision between these two blocks probably occurred during the Triassic (Lepvrier et al., 2004, 2008; Liu et al., 2012; Zhang et al., 2013; Kamvong et al., 2014; Faure et al., 2014; Roger et al., 2014; Halpin et al., 2015; Hieu et al., 2017; Rossignol et al., 2018; Thanh et al., 2019), even though various other ages such as Silurian–Devonian (Thanh et al., 1996; Findlay and Trinh, 1997; Thanh et al., 2011) or Carboniferous (Metcalfe, 2011, 2012) have been proposed.

A general stratigraphic framework for the Song Da and Sam Nua basins has been presented by Rossignol et al. (2018), in which the carbonate deposits of these two basins were succinctly described. The present study, based on 16 cross-sections located in the eastern part

of the Song Da and Sam Nua basins, focuses on the structural, stratigraphic, and sedimentological characteristics of these marine Triassic formations, with a particular emphasis on the carbonate platform deposits. We then compare the main characteristics of the Northern Vietnam platforms with other Triassic formations located in eastern Indonesia (Banda area; Villeneuve et al., 1994; Cornée et al., 1994; Martini et al., 1997, 2004).

2. Geological setting

The Indochina Peninsula is comprised of several continental blocks and volcanic arcs, separated by faults or sutures (Fig. 1). These continental blocks and volcanic arcs amalgamated together during various tectonic events that occurred from the Paleozoic to the Cenozoic (Ridd, 1971; Burrett, 1974; Metcalfe, 1988, 2011, 2013; Carter et al., 2001; Lepvrier et al., 2004; Carter and Clift, 2008; Ferrari et al., 2008; Faure et al., 2014, 2016; Burrett et al., 2014; Halpin et al., 2015).

In Northern Vietnam (Fig. 1), Cenozoic tectonic events are linked to the collision between the Indian subcontinent and the Asian plate and are marked by the Red River Fault (RRF) activity (Leloup et al., 1995). The Song Ma Suture, separating the Song Da Basin (southern part of the SCB) from the Truong Son Belt (northern part of the IB), is related to the Middle–Late Triassic Indosinian tectonic event (Lepvrier et al., 1997).

Many geodynamic models have been proposed to account for the development of the Indosinian orogeny (Fromaget, 1929, 1934; Ridd, 1971; Burrett, 1974; Metcalfe, 1988, 2011; Lepvrier et al., 2004; Ferrari et al., 2008; Faure et al., 2014, 2016; Burrett et al., 2014; Halpin et al., 2015; and references therein). In particular, many studies have focused on the Song Ma Suture (Lepvrier, 2004, 2008; Nakano et al., 2010; Lepvrier et al., 2011; Liu et al., 2012; Vuong et al., 2013; Roger et al., 2014; Faure et al., 2014, 2016; Lai et al., 2014; Shi et al.,

2015; Yan et al., 2017). Taking the stratigraphic evolution of the sedimentary basins flanking the Indosinian orogen into account, Rossignol et al. (2018) proposed a classical collisional system between the SCB and IB following the southward subduction, beneath the IB, of an oceanic crust from the Permian to the Middle Triassic period. Associated with this subduction, a volcanic arc emplaced onto the northern margin of the IB. Associated with this magmatic arc, the Sam Nua Basin developed as a retroarc foreland basin. The Song Da Basin, located in the southern part of the SCB, remained in a passive margin position until the beginning of the collision between the SCB and IB, when it was incorporated in a foreland system (as defined by Catuneanu, 2004).

Northern Vietnam (Fig. 2A) is comprised of three main domains (Tran Van Tri, 1973). A northern domain is delimited to the south by the RRF and mainly comprises Cambrian to Silurian deposits along with subordinate Permian and Triassic formations (Fig. 2A). A central domain is delimited to the north by the RRF and to the south by the Song Ma Suture (Fig. 2A). The Song Da Basin is located in this central domain, which is mainly characterized by NW–SE structures. To the south of the Song Da Basin, the Song Ma Suture consists of an ophiolitic mélange comprising lenses of serpentinized peridotite, gabbro, plagiogranite, diabase, and basalt enclosed within metasedimentary rocks (Hutchison, 1975; Trung et al., 2006; Thanh et al., 2011; Liu et al., 2012; Vuong et al., 2013; Zhang et al., 2014; Faure et al., 2014). Geochemical analyses indicate normal to enriched mid-ocean-ridge basalt affinities (Trung et al., 2006; Zhang et al., 2013, 2014) or supra-subduction zone ophiolite affinities (Thanh et al., 2011) for the mafic rocks. The Song Ma Suture underwent eclogite and high-pressure granulite facies metamorphism (Nakano et al., 2008, 2010; Zhang et al., 2013) during the Middle to the Late Triassic.

A southern domain located to the south of the Song Ma Suture hosts the Sam Nua Basin. This southern domain is marked by NW–SE structures to the west and SW–NE structures to the east. The northwestern part of the Sam Nua Basin contains various calk-alkaline magmatic rocks, which are either interbedded (volcanic) or intrusive (plutonic) into the Triassic sedimentary successions (Lepvrier et al., 2004; Hoa et al., 2008; Tri and Khuc, 2011; Liu et al., 2012; Faure et al., 2014; Shi et al., 2015). These calk-alkaline magmatic rocks are interpreted as being emplaced in an arc setting (Liu et al., 2012; Faure et al., 2014; Shi et al., 2015; Hieu et al., 2017).

Several unconformities corresponding to different tectonic and/or orogenic events have been recognized in the Cambrian to the Neogene lithostratigraphic successions of Northern Vietnam (Fig. 2B). In particular, a major unconformity, referred to as the Indosinian unconformity, occurred during the Middle to Late Triassic (Deprat, 1915; Fromaget, 1929, 1934; Lacassin et al., 1998; Lepvrier et al., 2004).

The stratigraphic succession of the Triassic deposits of the Song Da and Sam Nua basins has been established by Vu Khuc (1991), who differentiated three formations with respect to their macrofossil content such as mollusks, brachiopods, and ammonites. The Induan/Olenekian Tan Lac Formation is comprised of mainly shales, sandstones, and marls, and a minor amount of carbonates and volcaniclastic materials (Tri and Khuc, 2011; Thanh and Khuc, 2012). Various fossils, including bivalve, ammonoid, gastropod, and echinoderm remains indicate deposition during the Early Triassic in a marine environment. Above the Tan Lac Formation, the Anisian Dong Giao Formation is made up of limestones containing brachiopods, bivalves, ammonoids (Tri and Khuc, 2011; Thanh and Khuc, 2012), and foraminifers (Martini et al., 1998). Above the Dong Giao Formation, the Song Boi Formation,

which is similar to the Napeng Formation of Myanmar (Brunnschweiler, 1970), comprises a basal conglomerate followed by sandstones, siltstones, and shales (Tri and Khuc, 2011; Thanh and Khuc, 2012). Bivalve (Thanh and Khuc, 2012) and ammonoid fossils (Tri and Khuc, 2011) imply a marine depositional environment. Based on the fossil content, a Ladinian to Carnian age is attributed to the Song Boi Formation (Tri and Khuc, 2011; Thanh and Khuc, 2012). However, the ammonoid assemblage described in the upper part of this formation (Tri and Khuc, 2011) is probably of lower Norian age, instead of Ladinian–Carnian (Rossignol et al., 2018).

The current study aims to provide precise data on the stratigraphy, sedimentology, and structural arrangement of the Triassic formations of these eastern parts of Vietnam. For this purpose, we performed detailed investigations in two areas of the Song Da Basin, between the cities of Hoa Binh and Ninh Binh (Fig. 3A) and around the city of Ninh Binh (Fig. 3B). We also conducted similar investigations in the region of Vinh (Fig. 3C), located in the Sam Nua Basin.

3. Methodology

3.1. Structural investigations

Various localities in the Song Da and Sam Nua basins have been examined for structural analyses. Sixteen cross-sections (designated by Roman numbers in Fig. 3 and subsequent figures) were investigated: 12 are in the Song Da Basin (Fig. 3A and 3B) and four are in the Sam Nua Basin (Fig. 3C). The cross-sections were oriented perpendicularly to the main structures. In the Song Da Basin, we conducted fieldwork along the road from Hoa Binh to

Ninh Binh and in the Ninh Binh massif, also referred to as the "Dry Halong". In the Sam Nua Basin, most of the investigations were realized along the coastal roads between Thanh Hoa (to the north) and Vinh (to the south). In each basin, the different stratigraphic units identified (hereafter referred to as "members" and designated by lowercase letters and black circled numbers in Fig. 4 and subsequent figures) are correlated using intersecting cross-sections (e.g., sections VI and IX; Fig. 3B). When this was not possible (e.g., sections XV and XVI; Fig. 3A), the correlations between the different members were performed using the biostratigraphy (foraminifers) from the samples collected along these sections**.** The red-circled numbers in Fig. 4A and subsequent figures designate these samples.

3.2. Petrography and biostratigraphy

Limestone samples were collected from the best-preserved portions of the outcrops, avoiding recrystallized and fractured lithologies as much as possible. A total of 163 samples were collected: 131 from the Song Da Basin (Fig. 3A) and 32 from the Sam Nua Basin (Fig. 3C). The microfacies and biostratigraphic analyses are based on the observation of more than 39 thin sections (2.3 × 4 cm) under transmitted light (Zeiss Axioskop microscope). Additionally, eight samples were imaged by cathodoluminescence (CL) microscopy to reveal both specific sedimentological features and microfossils not visible in transmitted light. A Cl8200 MK5-optical CL with a cold cathode was used with beam conditions of 15 kV at 50–60 mA and an unfocused beam of approximately 1 cm. The observation chamber had a residual pressure of 80 mTorr. The samples were not coated. The parameters were kept fixed to avoid additional treatment. No filter or standard was used for image calibration. Microfacies were determined according to the sedimentary components and textures using the classification by Dunham

(1962), supplemented by that of Embry and Klovan (1971). A total of 19 samples were examined for their microfossil contents (mainly foraminifers). Only two were devoid of microfossils and 17 could be used for biostratigraphic determinations, among which nine were from the Song Da Basin and eight were from the Sam Nua Basin.

4. The Song Da Basin

The Song Da Basin, as defined by Tri and Khuc (2011), extends from Ninh Binh (SE) to the Dien Bien Phu Fault (NW) (Fig. 2). It is bounded to the south by the Song Da Fault and to the north by the RRF and comprises a heterogeneous basement made up of metamorphic and sedimentary rocks of various ages (Than and Khuc, 2012, and references therein).

4.1. Cross-section analyses and lithostratigraphy of the units

The investigated sections are located along the road from Hoa Binh to Ninh Binh (Fig. 3A) and in the Ninh Binh massif (Fig. 3B). Twelve cross-sections have been logged in this part of the Song Da Basin.

The S–N oriented ***cross-section A–B*** (Fig. 4, combined sections II and V in Fig. 3A) is located between the Ha Binh (or Ha Trunc) village to the south and the Phu Ly village to the north. The Ordovician–Silurian basement is exposed to the south, around the Ha Binh village. The youngest deposits, corresponding to the upper levels of the upper limestone members (members 24 and 25), are exposed to the north around the Phu Ly village. Several structures have successively been investigated, namely, from south to north: the Bim Son and Dong Giao synclines, the Tam Diep sheets, the “Dry Halong” massif (Ninh Xuan massif),

exhibiting a suite of gentle synclines and anticlines, and the Cu Gian Khuat structure with a reverse fold (V25). The southern Ordovician–Silurian massif consists of a succession of anticlines and synclines showing a strong deformation. The main shrinking process is absorbed by the numerous thrusts that occur mainly out of the main carbonate massifs, allowing to reconstruct a detailed lithostratigraphic succession. However, owing to the numerous thrusts and the scarcity of exposures, the complete succession requires some correlations between several cross-sections.

The synthetic stratigraphic succession contains five units (I to V) and 24 members. Unit I corresponds to the Ordovician–Silurian basement exposed around the Ha Binh village. Unit II is mainly exposed along ***cross-section VI*** (Fig. 5A), where seven members (denoted b to h in Figs. 5B, 5C, and 5D) have been distinguished. The first member of this unit (member a) is not exposed in this section but in section XV.

Unit III is well exposed along ***cross-section XV*** (Man Duc village, Fig. 6A) to the south of the Muong Khen crossroad (Fig. 3B). Three members (denoted a, d, and e in Fig. 6B) have been distinguished in Unit III.

Units IV and V are exposed along ***cross-section X*** (Hao Lu, Fig. 7A). Unit IV comprises only two members (denoted e and f in Fig. 7B) and Unit V is made up of two other members (denoted a and b in Fig. 7B).

The 12 lithostratigraphic logs (I to XVI), derived from the logging of the 12 sections, are shown in Fig. 8. To facilitate the correlations between the sedimentary sections, we attributed the same number (from 1 to 24) to each member of each unit. The thickness of each unit can be estimated despite the local tectonic effects, except for Unit I. Units II, III, IV and

V are more than 200 m, 300 m, 300 m, and 350–400 m thick, respectively. One of the main goals of our work is to provide similar marker levels for every section across the studied area.

4.2. Biostratigraphy

In the investigated area, only two radiometric studies have been performed by U-Pb dating on zircon grains. The first one was conducted on a granitic pluton that crosscuts the limestones of the Dong Giao Formation (Mong et al., 2004), which yielded an age of 242.4 ± 2.2 Ma (Hoa et al., 2008). The second radiometric study was conducted on sandstones from the lower Tan Lac Formation of the Muong Khem area (Unit II, section VI, Fig. 6) by Rossignol et al. (2018), which gave a maximum depositional age of 243.1 ± 2.3 Ma. Thus, the Tan Lac Formation appears to be deposited after the youngest zircon age (243.1 ± 2.3 Ma), indicating a Middle Triassic deposition. However, our biostratigraphic investigations based on benthic foraminifers gave an Olenekian/Induan age for samples V10, V140, and V143 (members 16 and 17); an Anisian age for sample V140 (member 17); a late Anisian age for samples V144 (member 18), V93 (member 19), and V12, V95, and V98 (member 20); and an Anisian/Ladinian age for sample V78 (member 21). Members 19, 23, and 24 did not yield any suitable microfossils for biostratigraphic dating. A list of foraminifers related to these samples is presented in Annex I. Consequently, a synthetic chronostratigraphic log can be proposed by merging lithostratigraphic and biostratigraphic data (Fig. 9). Units II (members 3 to 10) and III (members 11 to 15) are considered as Early Triassic; Unit IV (members 16 to 21) and the base of Unit V (member 22) are ascribed to the Middle Triassic (Anisian/Ladinian). The upper part of Unit V was deposited between the Ladinian and the Late Triassic.

4.3. Petrology, diagenesis, and sedimentology

Unit I. Because of the small number of outcrops, only two facies have been recognized in the Paleozoic basement: **(**1) tuffs, shales, sandstones and strongly deformed quartzites (Fig. 10A) and (2) thick beds of gray limestones.

Unit II. From the base to the top, member 3 yielded samples V8b and V136, which correspond to alternations of red shales and sandstones; members 4 and 5 are composed of gray limestones with bioturbations and a lumachel containing gastropods (V92); member 9 corresponds to an alternation of marls and nodular limestones (V90), and member 10 consists of limestones (V91) (Fig. 10B).

Unit III. This unit comprises shales interbedded with limestones, limestone beds increase upward. From the base to the top, the unit is made up of member 11 with conglomerates and massive, black, laminated limestones (V9 and V137), member 12 with micritic black limestones (V131), and member 13 with gray pink bioclastic limestones (V132). Members 14 and 15 are made up of black limestones with bioclasts. Thin beds of bioturbated shales containing a lumachel of gastropods are associated with a succession of gray marls and nodular limestones.

Unit IV. The base of this unit consists of member 16, which is composed of black laminated limestones (V10 and V141) (see also Martini et al., 1998) showing microbialitic structures. Above is member 18, which is made up of black limestones with remnants of Dasycladacean algae (V144). Member 19 is composed of dark gray micritic limestones with recrystallized microfossils (V93), and member 20 consists of homogeneous micritic limestones with foraminifers (V12, V94, V95, V96, and V97). The top of Unit IV consists of member 21, which is made up of recrystallized limestones with foraminifers (V78).

Unit V. Two members compose this unit: at the base, member 22 is made up of bioclastic limestones (V80). Above, member 23 is made up of black micritic limestones (V82) (Fig. 10C).

In summary, the lithological characteristics and the microfacies occurring in units II to V indicate that the limestones deposited on a wide, shallow water carbonate shelf, under low energy conditions. For Unit II, the terrigenous input, together with bioturbations and gastropods, could indicate a protected coastline. The algal laminations and conglomerates in the basal part of Unit III indicate temporary and local intertidal conditions. Accordingly, we propose a deposition on a low-angle carbonate ramp located in a marginal basin. The thickness of the deposits (hundreds of meters), together with constant shallow water settings along the entire succession, suggests that the basin underwent a rapid subsidence. Moreover, the Anisian carbonate ramp is younger in age from south to north.

4.4. Tectonics

The tectonic styles are closely related to the lithology of the units. **Unit I** (V13 and Vm1) shows very strong deformations in shales and tuffs (Fig. 10A). The fold axes are oriented E–W (N90°) and axial foliation is nearly vertical. This is likely related to Triassic structural styles because they are not found in the overlying sedimentary deposits.

Units II and **III** show beds with gentle dips to the south (N120°/SW50°), whereas station V20 displays a thrust to the north, which seems to be a characteristic of this unit. **In Unit IV** (V76 to V78, cross-section X, Fig. 7), the beds gently dip to the north. Cross-section A–B (Fig. 4) exhibits large open folds in the carbonate platform. However, locality V23A (Fig. 10D) displays internal thrusting from east to west. These thrusts are associated with

north–south axial folds similar to the Dinh anticline (cross-section VI, Fig. 4). **Unit V** (cross-section X, Fig. 7) shows gentle dips to the north. However, the thrust here is from north to south. To summarize, two types of structures are observed: large NW–SE folds, following the main trend of the belt, and secondary N–S folds, associated with northward thrusting and indicating an E–W shrinking. The main movements are toward the north. Nevertheless, southward, reverse faults in the limestone units are also present and could indicate a "jurassian-like" folding style associated with a "décollement" process at the shale/carbonate contact.

4.5. Summary

In their last paper devoted to this basin, Rossignol et al. (2018) took the entire basin into consideration and delineated five formations with, from the base to the top: the Co Noi (equivalent to the Tan Lac Formation) (Induan/Olenekian), the Dong Giao (Anisian), the Nam Than (early Ladinian), the Song Boi (early Norian), and the Suoi Bang (late Norian/Rhaetian). The Dong Giao Formation mainly consists of limestones. Other formations are essentially made of siliciclastic and argillaceous members. In the eastern area of central-northern Vietnam, only the upper parts of the Co Noi Formation (or Tan Lac Formation) and the Dong Giao Formation have been distinguished based on the stratigraphic framework provided by Rossignol et al. (2018) (after Tri and Khuc (2011) and Thanh and Khuc (2012)). Figure 10 from Rossignol et al. (2018) presents a simplified succession of the Dong Giao Formation, which corresponds to our Unit IV and members 16 to 21.

The depositional environments of Units II to IV are indicative of a marine passive margin setting with regular subsidence. However, a moderate tectonic impact and a weak

metamorphism indicate that this passive margin subsequently underwent "jurassian-like" deformations, similar to those described in the Jurassian Belt in front of the Alpine Belt, which is not consistent with a collisional environment. The main tectonic shrinking was accommodated by thrusts that are well developed in units I and III but moderately developed in units IV and V.

5. The Sam Nua Basin

The Sam Nua Basin is an elongated NW–SE trending basin located south of the Song Da Basin. It is delimited to the south by the Song Ca Fault, to the north by the Song Ma Fault, and to the west by the Dien Bien Phu Fault (Fig. 2). The basement of the basin comprises Neoproterozoic to late Cambrian metasedimentary rocks with high-grade metamorphism and late Silurian to Devonian metasedimentary rocks with low-grade metamorphism and strong deformations (Tri and Khuc, 2011). The Nam Co area, between the Song Da and the Sam Nua basins, comprises eclogites that underwent a high granulitic metamorphism (Nakano et al., 2008, 2010). These units represent the internal zone of an orogen ascribed to the collision between the IB and SCB (Faure et al., 2014). The Sam Nua Basin sediments include calk-alkaline magmatic rocks interpreted as being emplaced in an arc setting (Faure et al., 2014; Shi et al., 2015).

5.1. Cross-section analyses and lithostratigraphy of the units

Four main cross-sections oriented perpendicularly to the main structures have been studied in the eastern part of the Sam Nua Basin (Fig. 3C).

Cross-section XI (Fig. 11). This SSW–NNE section is located between Phung Luat to the south and Ho Truong to the north. It intersects several limestone structures: the Yen Li monocline, the Cau Gia (Quynh Lu and Dien Bien samples) anticline, the My Hung syncline, the Nui Thong Lim anticline, and the Hoang Mai and Nui Bom synclines. The local succession is composed of three units: Unit II with one member (denoted a in Fig. 11B), Unit IV with five members (denoted a and c to f in Fig. 11B), and Unit V with two members (denoted a and b in Fig. 11B). The thickness scales for the units are given in Fig. 11.

Cross-section XII (Fig. 12). This NW–SE cross-section is located between the Nghia Dan and Quynh Long villages. From west to east, three main structures are present: the Ru chop Binh monocline with an eastward dip, the Dien Binh syncline, and the Quynh Lu anticline. Two main lithologies have been recognized: green claystones and gray limestones. The lithological succession exposed in this area contains three units. From the base to the top, these units are: Unit II with two members (denoted a and c in Fig. 12B), Unit III with one member (denoted a in Fig. 12B), and Unit IV with two members (denoted a and c in Fig. 12B).

Cross-section XIII (Fig. 13). This WSW–ENE section, extends from the village of Do Luong to the village of Dien Chau. From the west to the east, the section crosses the Hao Son syncline, the Vinh Thanh monocline with a dip toward the east, and a metamorphic basement close to the Dien Chau crossroad. The change of the main structural directions, from NE–SW to NW–SE, occurs between the localities of Vinh Thanh and Hao Son. The local lithological succession comprises a metamorphic basement ascribed to Unit I and limestones interbedded with marls ascribed to Unit III, which is made up of five members (denoted a to f in Fig. 13B).

Cross-section XIV. This NW–SE cross-section is following the road joining the villages of Do Luong, Nam Dan and Vinh. This section exhibits metamorphosed rocks, with a general dip to the west and a vertical foliation. No fossils have been found and no radiometric data are available to date these supposed Triassic formations (Tran Van Tri, 1973). We assigned these formations to Unit I, although we recognize that a metamorphic marker cannot be used for any stratigraphic correlations.

Seventeen members can be defined in the Sam Nua Basin based on correlations and comparisons between the cross-sections and their lithological successions. With regards to the Song Da Basin, the same number has been attributed to the members of each cross-section (Fig. 14).

The total thickness of the Sam Nua Basin succession cannot be precisely evaluated due to the lack of sequences related to tectonic events. However, the estimated thickness of Unit II is more than 300 m, whereas units III, IV and V are approximately 400 m, 300 m, and 300 m thick, respectively.

5.2. Biostratigraphy

As far as we are aware, no radiometric data are available in the eastern part of the Sam Nua Basin, except for a dated rhyolite exposed in the southern part of the basin, which gives an age of 251.9 ± 1.7 Ma (Shi et al., 2015). Thus, the chronostratigraphic attribution is based on macrofossils and foraminifers. The foraminifer association assigns sample V101 (Vinh Thanh locality, cross-section XIII, Unit III, member 10) to the Olenekian/Anisian. Samples V104 to V106 (Quinh Lu locality, cross-section XII, Unit IV, member 12), V122 (Hoang Mai locality, cross-section XI, Unit IV, member 13), and V126 (Ho Thuong locality, cross-section XI, Unit

IV, member 14) are ascribed to the Anisian. Sample V121 (Hoang Mai locality, cross-section XI, Unit V, member 16) has an Anisian–Ladinian age, whereas sample V127 (Ho Thuong locality, cross-section XI, Unit V, member 17) is attributed to the Carnian. Therefore, units II and III belong to the Olenekian/Anisian transition, whereas Unit IV is Anisian in age. The base of Unit V is attributed to the Anisian/Ladinian transition. The upper part of Unit V is Carnian in age. In the Sam Nua Basin, Unit I cannot be dated and the Ladinian stage is not clearly identified.

5.3. Petrology, diagenesis, and sedimentology

Unit I. This unit is composed of a mix of tuff, shales, red sandstones, and conglomerates. All of them exhibit a schistosity and present a low-grade metamorphic facies. These rocks are attributed to the Cambrian to Silurian basement (Tran Van Tri, 1973).

Unit II. This unit is made up of an alternation of green siltstones, sandstones, and volcanic tuffs interbedded with siltstones. Member 2 is mainly composed of siltstones and marls. Member 3 contains beds of sandstones (Fig. 15A) with ammonoids. Member 4 is mainly calcareous and member 5 is a marly limestone.

Unit III. Several members have been recognized in this calcareous unit: member 6 is made up of green claystones and sandstones (V116D). Member 7 consists of gray limestones. Member 8 (V117) is made up of black limestones while member 9 (V118) is made up of siltstones. Member 10 (V98 to 102) is made up of gray bioclastic limestones.

Unit IV. This pure calcareous unit comprises member 11 (V109 and V110), which consists of well-bedded micritic limestones (Fig. 15B). Member 12 (V104 and V107) is a gray bioclastic

limestone. Member 13 (V122) is a gray micritic limestone. Members 14 (V126) and 15 (V127) are made up of gray bioclastic limestones.

Unit V. Member 16 (V120 and V121) is comprised of bioconstructed algal limestones (Fig. 15C) and member 17 (V127 and V128) is made up of bioclastic limestones.

The CL analyses performed on the samples from the two basins reveal close similarities between the diagenetic evolution of the limestones from the Song Da and Sam Nua basins. Two main comparable diagenetic phases have been recognized in the Sam Nua Basin (e.g., Unit III, member 10, V102) and the Song Da Basin (e.g., Unit IV, member 21, sample V95). The first diagenetic phase affected the sediments before their complete lithification. This early diagenetic synsedimentary event is linked to the circulation of an autochthonous interstitial fluid in a geochemically closed system. The permeability was significantly reduced during this phase, preventing further fluid circulation and late cement precipitation. A second diagenetic phase, corresponding to a late diagenetic event, is only recognizable in the fractures related to late tectonic activity and/or in the rare dissolution cavities (i.e., dissolved organisms).

5.4. Tectonics

The main structures evidenced in this part of the basin exhibit NW–SE or N–S directions. The tectonic style is very similar to the one exposed in the Song Da Basin with a succession of anticlines, monoclines, and synclines. In this part of the Sam Nua Basin, the dips of the beds are larger (50 to 60°) than those identified in the Song Da Basin. Remnants of NE–SW structures occur in the main NW–SE bands, as observed in the V127 outcrop, in the Hoang Mai and Ho Thuong localities (corresponding to samples V121 and V126). Moreover, we

observed remnants of N–S foliation in the Hung Nguyen quarry close to the city of Vinh, and a secondary foliation oriented NW–SE cross cutting NE–SW structures of Vinh Than (cross-section XII). This suggests that the NE–SW structures are older than the NW–SE ones. Outcrop V109 (cross-sections XI and XII) displays a good example of these NE–SW folds (Fig. 15D).

5.5. Summary

Our investigations show that the Triassic formations of the Sam Nua Basin present a basal, mainly siliciclastic unit, as well as two upper units that are mainly calcareous. As in the Song Da Basin, five units, comprising 17 members, have been defined. The carbonate deposits in the Sam Nua Basin are younger from south to north (Fig. 14), which could indicate a transgressive pattern with a retrogradation from south to north. The southern part is more metamorphosed than the northern one. The deformations indicate that the NE–SW structures are possibly older than the NW–SE ones, at least in the southern part of the study area. Correlations with the central and western part of this basin (Tri and Khuc, 2011; Thanh and Khuc, 2012; Rossignol et al., 2018) allow us to attribute units II and III to the Dong Trau Formation. However, it is important to note that Unit III is more calcareous than the other deposits of the Dong Trau Formation described elsewhere (e.g., Tri and Khuc, 2011; Thanh and Khuc, 2012; Rossignol et al., 2018). Unit IV likely corresponds to the upper part of the Dong Trau Formation and/or to the Hoang Mai Formation (Son et al., 2005). Unit V could be younger than the Dong Trau Formation. The counterpart of the Suoi Bang Formation (late Norian/Rhaetian) has not been documented in this eastern part of the basin.

6. Discussion

There are very few differences between the stratigraphic successions of the opposite margins of the Sam Nua and the Song Da basins. Both comprise Anisian to Carnian carbonate platforms with black micritic limestones at the base and light gray, mainly bioclastic limestones toward the top. However, we note that black micritic members can occur elsewhere at the top of the Song Da Basin successions. Both carbonate platforms exhibit similar sedimentary characteristics and biostratigraphic contents, including foraminifers, oncoids, red nodules, diverse bioclasts, algal laminations, and bioturbations. The bioclastic facies are interbedded with apparently azoic micritic members. Both sedimentary successions have similar large thicknesses: 1200 m for the Song Da Basin and ca. 1300 m for the Sam Nua Basin. Finally, both reflect rather similar depositional environments corresponding to subtidal to supratidal conditions in an inner platform. The thickness of the deposits and their overall similar depositional environments suggests that both platforms underwent steady subsidence.

Even if we cannot demonstrate that the Sam Nua Basin belongs to an active margin, with remnants of a calk-alkaline volcanic arc as assumed by several authors (Liu et al., 2012; Faure et al., 2014; Shi et al., 2015; Rossignol et al., 2018), we note that the carbonates in the Anisian to Carnian Sam Nua margin retrograded toward the north, similar to the Anisian/Carnian carbonate platform of the Song Da Basin (Rossignol et al., 2018 and Figs. 18 and 19 within). This favors the hypothesis of a convergence and suturing of the two margins. The Sam Nua margin uplifted northward while the Song Da margin was drowned northward (uplifted from south to north). This hypothesis has already been put forward for the time equivalent Nanpanjiang carbonate platform (Lehrmann et al., 2005a), which Lehrmann et al. (2005b) have suggested is being progressively drowned northward under the influence of the

growing Indosinian orogen (Lehrmann et al., 2005b). Even if our study does not allow to clearly identify an accretionary prism or a volcanic arc (despite the occurrence of some volcanic remnants in Unit II in the Sam Nua Basin), the timing, depositional environment, and subsidence patterns evidenced in the studied areas are consistent with a southward subduction of the Song Ma sea floor followed by a collision between the IB and SCB (Lepvrier et al., 2011; Liu et al., 2012; Vuong et al., 2013; Roger et al., 2014; Faure et al., 2014, 2016; Lai et al., 2014; Lehrmann et al., 2015b; Shi et al., 2015; Rossignol et al., 2018). This southward subduction is consistent with the location of a continental arc, marked by the occurrence of calk-alkaline rocks (Liu et al., 2012; Faure et al., 2014; Shi et al., 2015; Hieu et al., 2017) onto the northern IB. In addition, no significant unconformity has been identified between units II and III (Fig. 10B), supporting the hypothesis that a major tectonic event did not occur before the deposition of Unit III.

Another aim of this study is to improve our knowledge about the Triassic carbonate platforms of Northern Vietnam in order to compare them with other Triassic carbonate platforms in Southeast Asia and Indonesia. Indonesian Triassic carbonate platforms have been reported in eastern Sulawesi (Martini et al., 1997), Sinta Ridge in the Banda Sea (Villeneuve et al., 1994), as well as the islands of Seram (Martini et al., 2004), Buru and Misool. There, the main Triassic platforms developed in the Late Triassic (late Norian to Rhaetian) and were part of a discontinuous shallow water reef platform. The carbonates deposited in these platforms contain foraminifers and palynomorphs with Australian/Southern Tethys affinities. The thickness of the carbonate deposits is less than 250 m (250 m in eastern Sulawesi and 200 m on Seram Island). These Norian to Rhaetian reef carbonate platforms rest upon Upper Carnian to Norian micritic or marly limestones and are capped by latest Triassic to Early Jurassic intertidal to pelagic deposits. According to Villeneuve et al. (2010), the block

comprising these platforms came from a northern extension of the Irian Jaya Block. With respect to the eastern Indonesian Triassic platforms, the Vietnamese ones are older, thicker and reflect margins with higher subsidence. The contrasting subsidence patterns shown by the northern Vietnam and Indonesian basins likely reflect different tectonic settings and/or a different rheology of the basements of these basins.

7. Conclusions

This study reports new structural, sedimentological, and biostratigraphic (foraminifers) data for the Triassic formations of the eastern parts of the Song Da and Sam Nua basins based on an examination of four and 12 cross-sections in the Sam Nua Basin and Song Da Basin, respectively. The main results are as follows:

1) Two new detailed synthetic stratigraphic successions of the Triassic formations are provided. These stratigraphic successions have been established through consistent correlations between the different cross-sections. Five units and 23 members have been characterized for the eastern part of the Song Da Basin, and five units and 17 members have been identified in the Sam Nua Basin.

2) New biostratigraphic investigations based on benthic foraminifers improved the chrono-stratigraphic constraints for both basins, allowing us to compare the evolution of the carbonate platforms in the Song Da and Sam Nua basins from the Ladinian to the Rhaetian.

3) Sedimentological analyses provide relevant information on the depositional environments of these formations, reflecting two distinct margins that successively underwent low and high energy conditions.

4) Structural investigations point to differences in the relationships between the NW–SE and NE–SW structures.

5) Tectonic studies argue for a northward deformation vergence, favoring a northward obduction of the Song Ma rift and thus a northward collision between the IB and SCB. However, the evolution of the carbonate platforms alone cannot be used to support any of the geodynamic models although a northward migration of the deposits is not inconsistent with a northward collision.

6) Comparison of the Northern Vietnamese Triassic carbonate platforms with other Triassic carbonate platforms exposed in surrounding countries, particularly those of eastern Sulawesi (eastern Indonesia), should be developed to improve our paleogeographic and geodynamic knowledge of the whole of Southeast Asia during the Triassic period.

7) Additionally, our micropaleontological studies could help researchers understand the biological recovery that followed the end-Permian biological crisis.

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Appendices

Annex 1. List of foraminifers per basin and age of the associations.

Annex 2. Foraminifers (determinations are reported in Annex 1).

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Figure captions

Figure 1. Location of the main blocks and sutures in the Indochina Peninsula.

Main faults: MYF - Mae Yuam Fault, MPF - Mae Ping Fault, MF - Menxing Fault, NUF - Nan Uttaradit Fault, LF - Lincang Fault, DBPF - Dien Bien Phu Fault, RRF - Red River Fault, and SF - Sagaing Fault. Suture zones (definite or supposed): CM - Changning Menglian, JH - Jinghong, LP - Luang Prabang, SK - Sra Kaeo, NU - Nan Uttaradit, PK - Poko, and TK - Tamky (after Metcalfe, 2011, 2013 and Rossignol et al., 2016, 2018).

Figure 2. Simplified geological map of Northern Vietnam.

A. Simplified geological map (after Tran Van Tri, 1973 and Faure et al., 2014). The black rectangles indicate the areas investigated in this study. **B.** Simplified stratigraphic column of Northern Vietnam (after Tri and Khuc, 2011 and Thanh and Khuc, 2012). The wavy lines indicate the main unconformities.

Figure 3. Location of the cross-sections within the investigated areas.

The cross-sections are perpendicular with respect to the main structures.

A. Location of the cross-sections and outcrops investigated in the Song Da Basin between the cities of Hoa Binh and Ninh Binh. **B.** Detailed location of the investigated cross-sections around the city of Ninh Binh. The cross-sections are located on both sides of the Ninh Binh massif. **C.** Location of the cross-sections and outcrops investigated in the Sam Nua Basin between the cities of Than Hoa and Vinh.

Figure 4. Cross-section (II and V) from Ha Binh to Cau Gian Khuat.

A. Cross-section. Note the small dip and numerous thrust faults indicative of a northward motion. **B**. Stratigraphic series built with respect to the cross-section. The numbers of members are indicated with respect to the synthetic charts (Figs. 8 and 9).

Figure 5. Cross-section VI in the Dinh mountain area.

A. The cross-section is perpendicular to an N–S trending anticline. **B, C, D.** Local stratigraphic series with a correlative level. The numbers of members are indicated with respect to the synthetic charts (Figs. 8 and 9). Legend: see Fig. 4.

Figure 6. Cross-section XV in the Man Duc area.

A. Cross-section. Note the thrusts between units II, III, and IV. **B.** Stratigraphic series built with respect to the cross-section. The numbers of members are indicated with respect to the synthetic charts (Figs. 8 and 9). Legend: see Fig. 4.

Figure 7. Cross-section X in the area of the Hao Lu temples (Lei temples).

A. Cross-section outlined after the exposures shown in Figs. 10C and D. **B.** Stratigraphic series built with respect to the cross-section. The numbers of members are indicated with respect to the synthetic charts (Figs. 8 and 9). Legend: see Fig. 4.

Figure 8. Correlation between the members identified in the Song Da Basin.

The different members identified along the Song Da Basin have been correlated using intersecting cross-sections, where possible (see Fig. 3A and 3B), and through their biostratigraphic (foraminifers) content (see text for discussion).

Figure 9. Synthetic stratigraphic series of the Song Da Basin.

This synthetic stratigraphic succession is based on local stratigraphic successions. Corresponding cross-sections are indicated on the right side. Note that only the key biostratigraphic samples have been reported (see text for discussion). The stratigraphic chart and numerical ages are after Cohen et al. (2013). The thicknesses of the levels are estimates.

Figure 10. Photographs of the representative outcrops from the Song Da Basin.

A. Unit I (V13 = Ordovician, according to the geological map of Tri (1973). **B.** Unit II showing the contact between the red siltstones and carbonate levels. **C.** Unit V = part of the Hao Lu temple section (Fig. 7). **D.** Unit IV, northern part of the Hao Lu temple section.

Figure 11. Cross-section XI between Phung Luat and Ho Thuong.

A. Cross-section. Note the gentle anticlines and synclines. **B.** Stratigraphic series built with respect to the cross-section. The numbers of members are indicated with respect to the synthetic chart (Fig. 14). Legend: see Fig. 4.

Figure 12. Cross-section XII between Nghia Dan and Quinh Long.

A. Cross-section. Note the thrusts between Quinh Lu and Dien Binh. **B.** Stratigraphic series built with respect to the cross-section. The numbers of members are indicated with respect to the synthetic chart (Fig. 14). Legend: see Fig. 4.

Figure 13. Cross-section XIII between Do Luong and the Dien Chau road.

A. Cross-section. Note the lack of outcrops between the Van Thanh carbonates and the metamorphic outcrops shown in Fig. 15D. **B.** Stratigraphic series built with respect to the cross-section. The numbers of the members are indicated with respect to the synthetic chart (Fig. 14). Legend: see Fig. 4.

Figure 14. Correlation between the members identified in the Sam Nua Basin.

The different members identified along the Song Da Basin have been correlated using intersecting cross-sections, where possible (Fig. 3C) and through their biostratigraphic content (foraminifers; see text for discussion). An–La: undifferentiated Anisian–Lanidian stages. The stratigraphic chart and numerical ages are after Cohen et al. (2013).

Figure 15. Photographs of the representative outcrops from the Sam Nua Basin.

A. Unit II - railway trench close to Dien Binh. **B.** Unit IV - Quynh Lu outcrop. **C.** Unit V - Hoang Maï-Ho Tuong outcrop. **D.** Foliated limestones close to Dien Chau.

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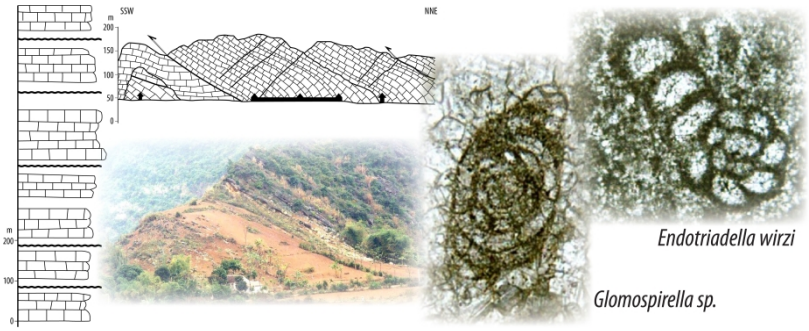

Highlights

- New investigations made in the Song Da and Sam Nua basins are presented
- Two new stratigraphic successions of the Triassic formations were established
- Shallow water carbonates platforms were identified in both basins
- Foraminifers associations indicate Early-Middle Triassic ages for these platforms

Declaration of Interest

We are very interested in the publication of this paper which gives a very detailed stratigraphic succession of the main Triassic carbonate platform in northern Vietnam. It is important to compare the evolution of the two basins on both sides of the Indonesian Song Ma suture in order to contribute to the geodynamical model of the Indochina and South Chine' blocs . Another aim is to perform important comparisons with the others Triassic carbonate platforms all around the Indochina peninsula.