INŻYNIERIA MINERALNA

CZASOPISMO POLSKIEGO TOWARZYSTWA PRZERÓBKI KOPALIN

2(52) 2023

NR 2(52) 2023, LIPIEC – GRUDZIEŃ

PL ISSN 1640 - 4920

POLSKIE TOWARZYSTWO PRZERÓBKI KOPALIN

POLISH MINERAL ENGINEERING SOCIETY

JOURNAL OF THE POLISH MINERAL ENGINEERING SOCIETY

NO. 2(52) 2023, JULY – DECEMBER

The Collision Between Indochina and South China Blocks in Northwestern Vietnam and its Controversy

Khuong The HUNG[1)], Jan GOLONKA[2)], Nguyen Khac DU[3)]

[1)] Hanoi University of Mining and Geology, Hanoi, Vietnam; e-mail: khuongthehung@humg.edu.vn (corresponding author); ORCID ID: 0000-0003-1544-6470
[2)] AGH University of Kraków, Kraków, Poland; ORICD: e-mail: jgolonka@agh.edu.pl; ORCID ID: 0000-0001-9671-5809
3) Hanoi University of Mining and Geology, Hanoi, Vietnam; e-mail: nguyenkhacdu@humg.edu.vn; ORCID ID: 0000-0003-1513-7600

http://doi.org/10.29227/IM-2023-02-18
Submission date: 20-08-2023 | Review date: 09-09-2023

Abstract

The Indosinian orogeny, which was regarded as the collision event between the South China and Indochina blocks that occurred in Southeast Asia, including Vietnam, resulting in the formation of the Indosinian mountain range. However, the question of how many times collision between these blocks occurred in the past and during which period remains unanswered. Furthermore, the closure of the ancient ocean and the evidence of its remnants between the South China and Indochina Blocks are still the subjects of serious debate. The underlying origin of the Indosinian thermo-tectonism is uncertain. The entire region was affected by the thermal-tectonic processes in the west, caused by the collision of the Sibumasu plate and Indochina block. The absence of evidence supporting the Indosinian as a significant mountain-building event is highlighted through an examination of regional paleogeography, as well as palaeontological and thermochronological data. There is no conclusive evidence to suggest that the Indochina and South China blocks collided during the Triassic times. A plate tectonic scenario that describes the Indosinian orogeny as a reactivation event triggered by the accretion of the Sibumasu block to Indochina is favored.

Keywords: *Indochina block, South China block, collision, Indosinian orogeny*

1. Introduction

For years, the collision between the Indochina Block (ICB) and South China Block (SCB) in Vietnam has been a subject of debate among geologists (Lepvrier et al., 2004; Maluski et al., 2001; 2005; Golonka et al., 2006; Faure et al., 2014; 2018; Thanh et al., 2018). Many assert that the collision took place during the late Permian - early Triassic, around 240 to 260 Ma ago, and it is thought to have significantly contributed to the formation of Vietnam's intricate geological structure (Hanski et al., 2004; Hoa et al., 2008, Hieu et al., 2013; 2017; Hieu, 2017). Moreover, the tectonic activities involving the ICB and ICB are notably intricate. Geological boundaries, which are defined as tectonic sutures representing the juncture of two geological blocks, have been identified in various locations within the ICB. At least three principal sutures have been recognized: 1) The Ordovician-Silurian Tam Ky - Phuoc Son suture, formed as a result of the amalgamation of the SCB and ICB (Tran et al., 2014; Gardner et al., 2017). 2) The Middle Triassic Song Ma suture zone, arising from the fusion of the ICB and SCB (Zhang et al., 2013); and 3) The Late Triassic suture, which emerged from the convergence of the ICB, SCB and Sibumasu blocks (Golonka et al., 2018). While some of these sutures have undergone extensive research, such as the Song Ma suture zone, others are in the initial stages of investigation. Notably, the Sibumasu and ICB interaction has garnered substantial attention in countries like Thailand, Cambodia, Malaysia, and Laos, but has been relatively understudied in Vietnam.

Nevertheless, there is a divergence of opinions among geologists regarding the collision's precise mechanism and timing. Some propose that the collision was a gradual process spanning millions of years, whereas others argue that it was a sudden, violent event. Additionally, there is controversy regarding the direction of the collision, with some suggesting that the ICB moved northward into the SCB (Hung, 2010), while others assert that the reverse happened (Maluski et al., 2001; 2005). Despite these debates, most geologists concur that the collision was a significant occurrence in Vietnam's geological past and continues to shape the country's landscape and natural resources to this day. The goal of this research is to provide a comprehensive outlook on the collision between the SCB and the ICB by investigating the potential timeframe of the collision and correlating the structures and geological formations in this tectonic zone. Furthermore, this research highlights the limitations that necessitate further exploration in the future.

2. Geological Background

East and Southeast Asia consist of various terranes and blocks that originated from the northern edge of Gondwanaland (Leloup et al., 1995, 2001; Findlay, 1997, Findlay & Trinh, 1997; Nam, 1998; Fan, 2000; Carter et al., 2001; Golonka et al., 2006). Continental blocks were created through successive rifting and breakup in the Palaeozoic and Mesozoic eras, leading to the northward movement and amalgamation of present-day Southeast Asia. The closing of Paleotethys between the blocks resulted in the creation of sutures such as Song Ma, Song Da, and Nan-Uttaradit (Metcalfe 1994, 1996, 1998, 2011; Golonka et al., 2006). Vietnam includes parts of the ICB and SCB. The SCB, which includes southern China and a northeast fragment of Vietnam, is separated from North China, ICB, the Sibumasu block, and the Songpan-Ganzi ac-

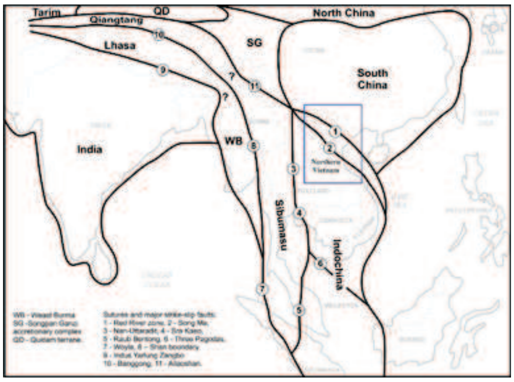

Fig. 1. Main plates and terranes of Southeast Asia and location of northern Vietnam (after Metcalfe, 1998; Golonka et al., 2006)

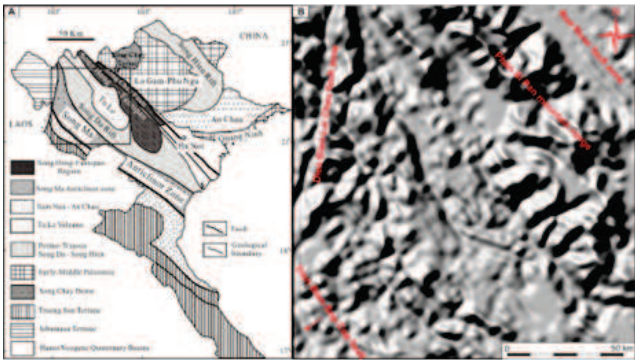

Fig. 2. A – Tectonic sketch map of northern Vietnam showing the location of the study area (after Tri et al., 1979). B – Northwestern Vietnam marked on the digital elevation model showing the Red River, Dien Bien-Lai Chau fault zones, Dien Bien-Sop Cop fault, and Phan Si Pan mountain range

cretionary complex by various sutures. The core of SCB was formed důing Precambrian times. The southeastern margin of South China is recently a passive margin connected to the South China Sea by an extended continental crust.

The ICB consists of Vietnam, Laos, Cambodia, western Thailand, and potentially other regions. It is separated from the SCB by the Song Ma suture and from the Sibumasu plate by various sutures (Fig. 1). The Ailao Shan-Red River (ASRR) shear zone caused significant sinistral displacement around 27±22 Ma and resulted in the tectonic structure of Northwestern Vietnam. The Song Ma belt, where mafic and ultramafic masses are located, separates ICB from SCB and is thought to be composed of ophiolitic fragments. Recent studies suggest that the Indosinian event, which caused regional metamorphism and magmatism, occurred around 250 Ma, indicating that the final suturing between ICB and SCB took place during the Early Triassic times. However, further research is needed to fully understand the Indosinian orogeny and its constituent rocks.

Vietnam is a country located in Southeast Asia, encompassing an area of discontinuous geology such as the Red River and Dien Bien – Lai Chau fault zones (Fig. 2). It is bordered by China to the north, Laos, and Cambodia to the west, and the East Sea (South China Sea) to the east and south. The area has distinct landforms varying from north to south due to climatic, tectonic, and lithological factors. The geology of the area comprises ophiolite complexes, intrusion complexes, volcanic rocks, and terrigenous and carbonate sedimentary rocks, with ages ranging from Proterozoic to the present. The scope of this research includes the study of the Song Hong (Red River), Song Da (Da River), Tu Le, Song Ma, and Sam Nua regions, which correspond to northwestern Vietnam. Northwestern Vietnam is bounded by the boundary between China and Vietnam to the north, the boundary between Vietnam and Laos to the south, the Red River fault to the east, and the Dien Bien-Sop Cop fault zone to the west.

3. Materials and methods

3.1. Sample collection and analysis methods

The authors conducted field work in several localities in Northwestern Vietnam. This work was focused on magmatics as well as sedimentary rocks and their tectonic relationship. The granitoids and ophiolite complexes crop out along the SCB and ICB boundary indicating various Paleozoic and Mesozoic collisional stages. The studies of tectonic deformation revealed several unconformities affecting both magmatic and sedimentary rocks, the details are provided in the discussion chapter.

In order to determine age, provenance and tectonic setting, approximately 5 kg of ultra-mafic to mafic rock samples were collected along National Highway 4G in the Song Ma area (Figs. 3, 4 & 5); are pulverized to a particle size of 0.5 mm, followed by a washing and rinsing process using deionized water to eliminate dust and lighter minerals. Zircon crystals are subsequently isolated from the heavy mineral fraction through a series of procedures that include drying, magnetic separation, and enrichment via bromoform solvent. Manual selection of zircon grains is then conducted under microscopic observation to identify well-formed grains with minimal or no inclusions. This entire sample preparation protocol is executed at Thuong Pho Analytical Technology Co., Ltd., located in Wuhan, China.

Zircon grains selected from sample SL-03 are affixed to an epoxy resin disc and polished until the central region of each grain is exposed (Fig. 6). This facilitates subsequent structural and compositional analyses, as well as cathodoluminescence

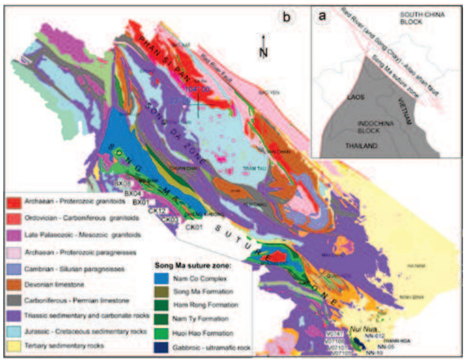

Fig. 3. (a) Geological map of the Paleotethys Orogen in southwest China and southeast Asian (modified from Jian et al., 2009) showing the main tectonic blocks and suture. (b) Simplified geologic map of Northwest Vietnam showing the Song Ma zone (after Bao & Luong, 1982)

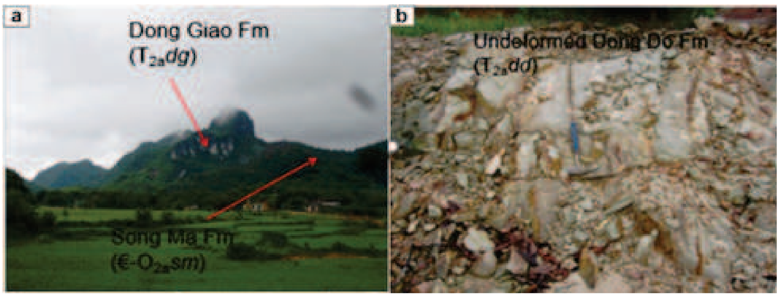

Fig. 4. (a) Limestone of the Dong Giao formation overlying the Song Ma formation (photo from Thanh et al., 2015); (b) Undeformed limestone of the Dong Do formation

(CL) imaging, which is performed using Scanning Electron Microscopy (SEM). Prior to CL imaging, the zircon samples undergo examination under a polarizing microscope, and reflected light micrographs are captured to identify optimal sites for U-Pb isotopic analysis. Care is taken to avoid regions with fractures or inclusions that could compromise the accuracy of age determinations (Fig. 6).

The U-Pb isotopic composition of the zircon is analyzed using a single-spot laser ablation technique, employing a laser with a 34-micrometer diameter, on an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). This analysis is conducted at the National Key Laboratory of the China University of Geosciences in Wuhan.

3.2. Paleogeographic reconstruction maps

The recontraction of main tectonic events enable to position ICB and SCB on the global paleogeographic maps. The global maps are constructed using a plate tectonic model, which describes the relative motions between approximately 300 plates and terranes (Golonka, 2007). His motion is based on the Euler theorem (Euler, 1736, 1741), each plate travels around the Euler pole - intersection of the Euler axis with the Earth's surface defined by latitude/longitude coordinates. The plate's movement is measured in degrees. The total distance of the plate relocation from a given ancient time until present constitutes the finite pole of rotation. The list of this finite poles of rotation for tectonic elements is contained in the rotation file. The examples of such rotation file are provided in Golonka (2007 and 2020) papers. The global paleogeography for Triassic times was reconstructed using this model (Figs. 7, 8).

4. Discussions

4.1. The collision between the SCB and ICB based on global plate tectonics and paleogeography

Krobicki and Golonka's (2008) examination of plate tectonics and paleogeography in Southeast Asia indicated that SCB and ICB were separated by deep-water basins containing thinned continental or possibly oceanic crust during the Ordovician times, which is supported by the presence of Ordovician-Silurian sediments and uplift and volcanic rocks (Hung, 2010). Shouxin and Yongyi (1991) reported that the southern part of SCB was covered by deep water synorogenic clastic deposits, which were also found on the margins of the ICB and known as the Pa Ham Formation in Northern Vietnam. These deep-water deposits were later replaced by shallow-water sedimentary formations, including the continental Lower Devonian red beds and Lower Devonian Nam Pia Formation composed mainly of terrigenous sediments and marl, medium-bedded to massive fine-grained limestone, representing shallow water sediments (Hung, 2010; Son et al., 1978). The Lower Paleozoic greenschists of deep-sea origin were unconformably covered in many localities by Devonian redbeds. The first time the ICB collided with the SCB during the collisional process is likely to have been in the Late Silurian-Early Devonian times (Golonka et al., 2023). The Song Chay complex granitoid is connected to this event. Plate tectonic reconstructions suggest that the Early Devonian deformation and uplift may be linked to the rifting of the SCB from Gondwanaland. This event may also be related to the global Caledonian orogenic event. After Devonian shallow-water sedimentary rocks, the area was covered by Carboniferous-Permian sequences, including limestone of the Carboniferous-Permian Bac Son formation, clay shale of the Lower-Middle Permian Si Phay formation, and limestone of the Middle Permian Na Vang formation. A new oceanic basin was formed between ICB and SCB during Late Permian times, recorded by the ophiolite belt consisting of Nui Nua, Bo Xinh, Chieng Khuong complexes, Huoi Hao formation, and perhaps ultramafic Ban

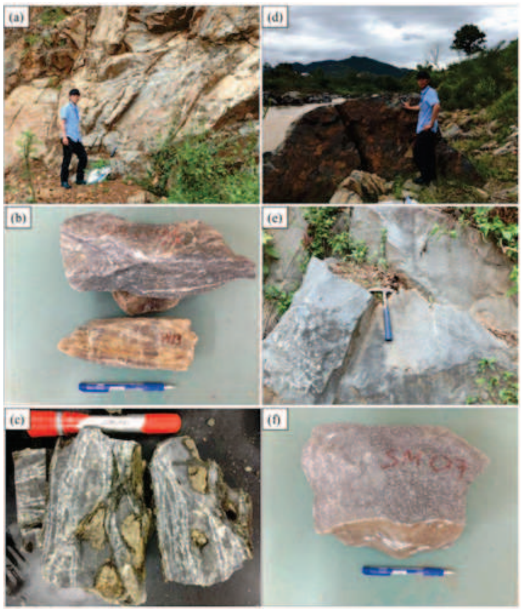

Fig. 5. (a, b, c) Outcrop and deformed samples of ultra-mafic to mafic rocks, with an age of 257±5.5 Ma, along National Highway 4G in the Song Ma area; (d, e, f) Outcrop and collected samples of ultra-mafic to mafic rocks along the Song Ma River, exhibiting undeformated, and with uncertain/intrusive age within the Huoi Hao formation (Fig. 6)

Xang complex. The origin of this basin is related to the Paleotethys Ocean's closure between Sibumasu and ICB by subduction below Indochina (Golonka et al., 2006; Hung, 2010).

According to the study conducted by Hieu (et al., 2014), the U-Pb zircon dating results of the intrusive gabbroic rock phase within the ultra-mafic rocks of Nui Nua complex indicate an age of 470 Ma. As a result, it can be deduced that the ultra-mafic block of the Nui Nua complex predates the Middle Ordovician times. Additionally, the presence of freshwater fish fossils in central Vietnam provides evidence supporting the connection between the ICB and SCB prior to the Middle Devonian times (Thanh et al., 1996).

In the Song Ma region, specifically in the Son La province, there are Triassic limestone deposits with considerable thicknesses reaching hundreds of meters. Notably, these deposits exhibit minimal disturbance from the Dong Do and Dong Giao formations (Figs. 3, 4). This observation implies that their formation took place in a passive continental margin setting, as opposed to an active continental margin.

During the survey conducted from Hanoi to Son La, various gabbroic blocks of relatively young age (257±5.5 Ma) were encountered (Figs 5, 6), along with other blocks that exhibit undeformation. This observation implies that these blocks were formed subsequent to the collision between the SCB and the ICB. The formation process is likely associated with extensional activities within the SCB during the Indosinian orogeny, gradually subducting beneath the Song Ma suture zone. These blocks now remain as fragments situated above smaller units. As a result, misconceptions have arisen regarding the chronological sequence of the older ophiolitic belt's formation.

The distribution of Triassic limestone in Vietnam is extensive, stretching from northwester Vietnam to Quang Binh province in the northeast direction, covering a distance of approximately 1000 km (Fig. 3). One notable characteristic of the Middle Triassic limestone is its predominant occurrence in the eastern part of Vietnam, rather than in the western part. This observation suggests a subduction model where the oceanic crust adjacent to SCB subducts beneath the ICB, contrary to the view presented by Hung (2010). However, explaining the relationship between SCB and ICB presents difficulties in accounting for the widespread distribution of Triassic limestone formations in the region. Therefore, the proposed model suggests that the passive continental margin environment on the SCB provides a more plausible explanation for limestone formation in this area, while limestone formation is absent on the ICB. Additionally, this model offers a more reasonable explanation for the presence of mafic, ultra-mafic, and basalt rocks in the Da River zone as result of plume mantles activity.

During the Permian times, a volcanic eruption occurred in the Song Da region, which is thought to be linked to the origin of the Cam Thuy and Vien Nam formations. The cause of this event is still the subject of hot debate. Some geologists argued that Cam Thuy and Vien Nam formations were perhaps related to the plate reorganization and mantle plume activity, known in China and Indochina as Emeishan plumes and related to Siberian basaltic traps (Hanski et al., 2004; Hoa et al., 2008; Krobicki & Golonka, 2008 and references therein). They were formed in within-plate (intraplate) settings, related to back-arcs spreading (Lepvrier et al., 1997, 2004; Golonka et al., 2006) or Song Da Rift of Tri (ed., 1979). The preferred geodynamic reconstruction assumes that this magmatism was formed during the convergence of the Sibumasu and the newly formed ICB-SCB. The oceanic crust was subducted southward under ICB (Hoa et al., 2008). This subduction led to the origin of Late Permian – Triassic magmatic events and Song Da volcanism (Hung, 2010).

Remnants of oceanic lithosphere were accreted into the northern edge of the IDB and appeared in the Song Ma fault zone and Sam Nua zone (Golonka et al., 2006; Trung et al., 2007 and references therein). The Indosinian orogeny of Fromaget (1937, 1941) represents the final stage of this closure. The orogeny was recorded by magmatic, metamorphic, and deformation events in Truong Son, Sam Nua, Nam Co, and Song Ma structural zones (Hutchison, 1989; Nam, 1998; Lep-

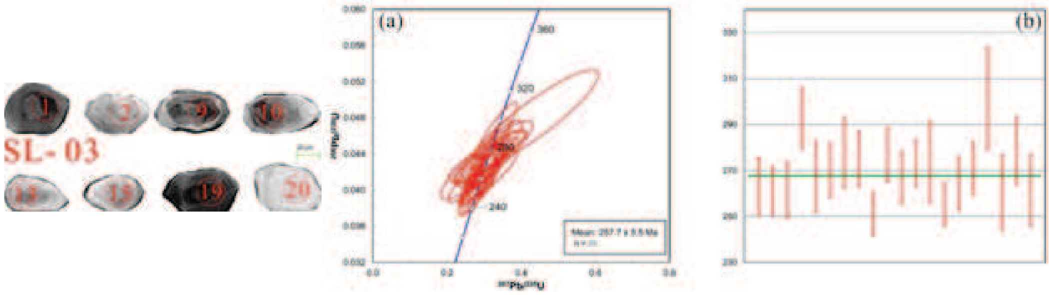

Fig. 6. The CL images of zircon crystals extracted from the SL-03 gabbro sample in the Song Ma area, Son La province, are accompanied by the corresponding locations of the analysis points using the LA-ICP-MS method; (a) The graphical representation illustrates the outcomes of the zircon U-Pb analysis conducted on the SL-03 gabbro sample, employing the LA-ICP-MS technique. (b) A schematic diagram is presented to depict the distribution of average ages observed in the dataset

Fig. 7. Global plate tectonic map of Late Triassic at 224 Ma ago. Molweide Projection. 1–oceanic spreading center and transform faults, 2–subduction zone, 3–thrust fault, 4–normal fault, 5–transform fault

vrier et al., 1997, 2004, 2008; Lan et al., 2000). The folded Triassic and older rocks were unconformably covered by Upper Triassic coal-bearing molasse beds of the Suoi Bang Formation. A plate tectonic scenario that describes the Indosinian as a reactivation event triggered by the accretion of the Sibumasu block to Indochina is preferred (Golonka et al., 2018). The new large Chinese-SE Asian plate including North and South China, Mongolia, and eastern Cimmerian plates was consolidated at the Triassic-Jurassic boundary (Figs 7, 8).

4.2. The collision between the SCB and ICB based on structural and collision timing

In northwestern Vietnam, the Song Ma structural zone is regarded as the "hinge" between the SCB and ICB (Dovijkov, 1965). The studied area is known as the Sam Nua-Hoanh Son pre-rift basin (Tung and Tri, 1992). The basin has an S-shape, bulging in the middle and narrowing at both ends. The northern end of the basin is adjacent to the western edge of the Song Ma fold belt. The Sam Nua-Hoanh Son basin underwent significant evolution during the Triassic, and it was filled with shallow marine sedimentary rocks of the Carboniferous-Lower Permian system, with a thickness of 1000-1500m (Bao & Luong, 1982).

According to Wang et al. (2021), the Vit Thu Lu calc-alkaline arc-like granodiorite and granite, along with the Thanh Long plagiogranite, have been dated to approximately 475-470 Ma (Bui et al., 2018). In the Huoi Tong massif in western Dien Bien area, the granitoids formed between 446 and 415 Ma (Nguyen et al., 2005). Monazite inclusions found in garnets from schist yielded a Sm-Nd isochron metamorphic age of 424 ± 15 Ma (Maluski et al., 2005; Tran et al., 2014).

These observations, combined with the regional angular unconformity between the Silurian and Devonian sequences located to the north of the Song Ma zone (Thanh et al., 1996; Janvier et al., 1997, 2003; Tran and Vu, 2011; Tran et al., 2014, 2020), provide evidence for the northward subduction and consumption of the Tam Ky-Phuoc Son Ocean, resulting in its accretion with the southern Yangtze in the Ordovician-Silurian times, approximately between 480-415 Ma. This geological process was also contemporaneous with the northward accretion of the Kontum terrane and its southern counterparts (Gardner et al., 2017; Tran et al., 2020).

Faure et al. (2018) utilized zircon and monazite U/Pb radiometric dating techniques to establish an age of approximately 250–240 Ma for the crustal melting process (Fig. 9). Concurrently, ductile shearing with a top-to-the-NW movement occurred, coinciding with the formation of the Ngoc Linh MCC. This period of extensional tectonics was succeeded by dextral strike-slip faulting at around 240–230 Ma, preceding the emplacement of two-mica granitic plutons at approximately 240–224 Ma. Additionally, in the Ngoc Linh and Kan Nack complexes, zircon and monazite analyses yielded U-Pb ages from the Early Paleozoic era. In the Kham Duc complex, a metamorphic event featuring garnet-biotite-staurolite-kyanite minerals occurred at around 460 Ma (MP/MT), followed by migmatites at approximately 450 Ma. The Dai Loc plutonic suite, dated to 420–400 Ma, and the Dien Binh calc-alkaline granodiorite, dated to 450–425 Ma, provide evidence of an Early Paleozoic geological event.

Zircon U-Pb dating of silicic igneous rocks in the Pingxiang area, southwest China, reveals that the rhyolites and biotite granites were emplaced at 251–250 and 249 Ma (Early

Triassic), respectively (Huang et al., 2023). By synthesizing all available data in conjunction with the regional tectonic evolution of the southwestern Youjiang Basin and adjacent regions, we ascribe the origin of the peraluminous A2-type rhyolites and biotite granites to the extensional setting that prevailed during oceanic subduction. This subduction was initiated by the rollback of the Paleotethys oceanic lithosphere around 251–249 Ma. This study underscores that subduction-related magmatism associated with the Paleotethys oceanic lithosphere remained active during the Early Triassic.

In Xu's (2023) study, granitoids within the SCB were investigated. The results revealed that Late Triassic granitoids exhibit a singular peak age of approximately 230 Ma and predominantly consist of granites, as evidenced in SiO_2 vs Na_2O+K_2O diagrams. The youngest U-Pb ages obtained from detrital zircons suggest a maximum depositional age ranging from 196 to 180 Ma (Meng et al., 2015; Xu et al., 2021). Furthermore, the NNE-striking structures were intruded by a Late Jurassic granitic pluton. Consequently, it is plausible that the NNE-striking eastern Hunan thrust belt might have formed during the Middle Jurassic.

Detrital zircon U-Pb dating results from eleven samples within the Ailaoshan-Song Ma suture zone reveal prominent age peaks at 245 Ma, 440 Ma, and 970 Ma, corresponding to tectonic events recognized in the SCB and ICB (Li et al., 2021). In-situ Hf isotopic analyses suggest that these Neoproterozoic and Early Paleozoic events indicate significant episodes of continental growth with mantle contributions. Along the suture zone, the ophiolitic mélange zone has been subdivided into three units, denoted as M1, M2, and M3, based on disparities in zircon age and Hf isotopic signatures. M1 exhibits two primary age groups, peaking at approximately 435 Ma and 970 Ma. The source of M1 is likely the Paleozoic sedimentary cover, predominantly Silurian sedimentary rocks from ICB, with a minor contribution from magmatic rocks within the ophiolitic mélange.

M2 is characterized by a dominant Late Permian (260 Ma) age group with $\varepsilon Hf(t)$ values ranging from -1 to +7 and a significant peak at approximately 0.85 Ga in model ages. The primary source of M2 is considered to be the Eastern Lhasa Indus-Yarlung Zangbo suture (ELIP) and related rocks in SCB, with a minor fraction of detrital zircons originating from recycled sedimentary rocks in ICB.

M3 exhibits a distinct Mesozoic age peak at 250 Ma, with $\varepsilon Hf(t)$ values ranging from -17 to -5 and two-stage model ages primarily concentrated in the range of 1.3 Ga to 1.8 Ga. M3 materials were primarily supplied from the magmatic arc in ICB (Western Ailaoshan-Truong Son belt), with a minor contribution from the southwest margin of SCB. The observed differences between these three units highlight significant lateral heterogeneity within the suture zone. These findings provide valuable insights into understanding the paleogeographic reconstructions of the postulated positions of Asian continental blocks from the Early Carboniferous to the Middle Triassic. Supplementary data related to this article can be accessed online at https://doi.org/10.1016/j.earscirev.2021.103789.

In the study conducted by Liu et al. (2023), they present findings concerning the heterogeneity within the Ailaoshan–Song Ma ophiolitic mélange. All examined samples exhibit a consistent zircon age spectrum, featuring two distinct age peaks at 430 and 960 Ma, which closely align with the characteristics of the previously identified M1 unit. These results suggest that the northwestern segment of the Ailaoshan ophiolitic mélange can be more accurately subdivided into two units, namely M1 in the interior and M2 in the exterior, as opposed to the previous classification. This observation underscores the presence of strike-perpendicular heterogeneity within the region. Furthermore, considering the geometries of these units, characterized by a northeast-dipping orientation, and their respective depositional ages (M1, 310–270 Ma; M2, 260–240 Ma), it becomes evident that the older M1 unit has been thrust upon the younger M2 unit. This indicates a tectonic inversion process..

M2 is situated within the northwestern segment and displays a solitary age peak at 260 Ma (Li et al., 2021). Conversely, M3 is distributed in the southeastern segment of the Ailaoshan–Song Ma ophiolitic mélange, with its most prominent age peak recorded at 245 Ma (Li et al., 2021). The distribution pattern of M1, M2, and M3 along the Ailaoshan–Song Ma ophiolitic mélange reveals a substantial heterogeneity, highlighting variations in provenance among distinct segments of the Ailaoshan–Song Ma Ocean (Li et al., 2021; Lin et al., 2022). These differing provenances of the three units correspond to the various evolutionary stages of the eastern Palaeo-Tethys (Li et al., 2021; Wang et al., 2021).

To sum up, there are varying views regarding the timing of the amalgamation of the SCB and the ICB, as well as the age of the Song Ma suture zone, which include the Permian-Triassic (Indosinian orogeny) and Silurian-Early Devonian (Caledonian orogeny). These issues require further elucidation.

Similarly to the Triassic volcanic formations, the Jurassic intrusive-volcanic complex of the Muong Hin-Ban Muong type also requires further detailed investigation. Some studies, based on geological relationships and structural features, have disputed the existence of Jurassic magma activity in the study area and instead have merged it into the Triassic magma complex (Truong, 1999). However, detailed research data for these formations is still very limited and lacks reliable quantitative data, especially for trace elements and isotopes. It is necessary to determine the U-Pb zircon isotope age for the Muong Hin volcanic formation and the Ban Muong intrusive volcanic features. Additionally, comparing their trace element geochemical characteristics with those of the middle Triassic magmatism (Dong Trau-Song Ma) would enable more definitive conclusions.

The Sam Nua depression basin is considered a unique tectonic-structural zone in the Truong Son fold belt (Dovjikov, 1965). While in the past, the Permian-Triassic granitoid without associated volcanic rocks were regarded as part of the basement of the Mesozoic north central Vietnam basin, the current perspective views the Nui Chua-Phia Bioc contrasting magma complex as a product of the continental crustal re-melting process (anatexis), similar to the Triassic volcanic-intrusive formations. As a result, the crystalline basement of the Sam Nua basin could be even older. Therefore, the evolutionary history of the north central Vietnam Mesozoic basin needs to be associated with modern tectonic concepts, particularly the linkage between the SCB and ICB.

Fig. 8. Global plate tectonic map of Late Triassic at 200 Ma ago. Molweide Projection. 1–oceanic spreading center and transform faults, 2–subduction zone, 3–thrust fault, 4–normal fault, 5–transform fault

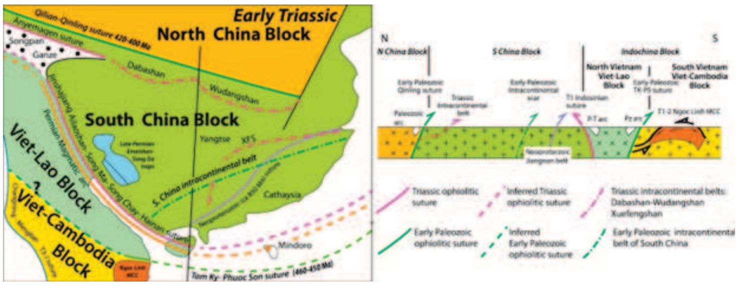

Fig. 9. Reconstruction of the ICB-SCB tectonic framework in Early Triassic. A: Palinspastic map after removing the Cenozoic sinistral strikeslip motion, and the Triassic dextral strike-slip along the late Indosinian faults. In this reconstruction, the Emeishan-Song Da LIP is about 1200 km from the Ngoc Linh MCC. B: schematic crustal scale cross section from N. China to Kon Tum massif (after Faure et al., 2018)

5. Conclusion

The complex tectonic, magmatic, metamorphic, and deformation events that took place and were overprinted in northwestern Vietnam have made it challenging to pinpoint the timing of the collision between SCB and ICB in the area. Despite the complexity of the geological events in this region, the current recorded evidence suggests that the timing of the collision is as follows.

During the Ordovician times, the SCB and ICB were separated by deep-water basins with thinned continental or possibly oceanic crust. The first collision between ICB and SCB possibly occurred during the Late Silurian-Early Devonian, leading to the formation of a new oceanic basin between the two blocks during the Late Permian times. This basin's origin is related to the subduction of the Paleotethys Ocean below ICB, and it is recorded by the ophiolite belt consisting of several complexes and formations. The Indosinian orogeny represents the final stage of this closure and was marked by magmatic, metamorphic, and deformation events in various structural zones. The orogeny was triggered by the accretion of the Sibumasu block to ICB, leading to the consolidation of a new large Chinese-SE Asian plate at the Triassic-Jurassic boundary.

The issues that require further clarification from the aforementioned explanations persist. For instance, there is limited evidence of oceanic crust remnants during the Early Devonian times. Specifically, the specific evidence for the Permian-Triassic magma period in northwestern Vietnam does not exhibit typical characteristics of mountain-building magma but rather is associated with an intra-plate geodynamic environment. To address this issue, it is necessary to clarify the nature of Triassic sedimentary-volcanic formations using quantitative data on their chemical composition, trace elements, and isotope content, which can be interpreted based on the principles of petrogenesis.

Acknowledgements

This research is supported by the Vietnam National Foundation for Science and Technology Development (NAFOSTED), under grant number 105.01-2020.13.

Literatura – References

1. Bao, N.X. & Luong, T.D., 1982. Geological map of Vietnam at 1:500,000 with a summary explanatory note. Geological Department of Vietnam, Ha Noi, 52 pp.
2. Bui, V.H., Kim, Y., Thanh, N.X., Tran, T.H., Yi, K., 2018. Neoproterozoic deposition and Triassic metamorphism of metasedimentary rocks in the Nam Co Complex, Song Ma Suture Zone, NW Vietnam. Geosciences Journal, 22 (4), 549–568.
3. Carter, A., Roques, D. & Bristow, C., 2001. Understanding Mesozoic accretion in Southeast Asia: Significance of Triassic thermotectonism (Indosinian orogeny) in Vietnam. Geology, 29: 311-314.
4. Dovjikov, A.E. (ed.), My, B.P., Vasilevskaia, E.D., Jamoida, A. I., Ivanov, G.V., Izokh, E. P., Huu, L.D., Mareitchev, A.I., Chien, N.V., Tri, N.T., Luong, T.D., Quang, P.V. & Long, P.D., 1965. Geology of North Vietnam. Explanatory note of the Geological Map of North Vietnam at 1:500,000 scale. Geological Department of Vietnam, Ha Noi, 584 pp.
5. Euler, L., 1736. Mechanica sive motus scientia analytice expositat. Academia Scientiarum, Petersburg, Russia. 546 pp.
6. Euler, L., 1741. Theorematum quorundam ad numeros primos spectantium demonstratio. Commentarii academiae scientiarum Petropolitanae, 8: 141–146.
7. Fan, P.F., 2000. Accreted terranes and mineral deposits of Indochina. Journal of Asian Earth Sciences, 18: 343-350.
8. Faure, M., Lepvrier, C., Nguyen, V.V., Vu, T.V., Lin, W., Chen, Z., 2014. The South China block-Indochina collision: Where, when, and how ?. Journal of Asian Earth Sciences, 79, 260-274.
9. Faure, M., Nguyen, V.V., Hoai, L.T.T., Lepvrier, C., 2018. Early Paleozoic or Early-Middle Triassic collision between the South China and Indochina Blocks: The controversy resolved? Structural insights from the Kon Tum massif (Central Vietnam). Journal of Asian Earth Sciences, 166, 162-180.
10. Findlay, R. & Trinh, P.T., 1997. The structural setting of Song Ma region, Vietnam and the Indochina - South China plate boundary problem. Gondwana Research, 1: 11-33.
11. Findlay, R., 1997. The Song Ma Anticlinorium, northern Vietnam: The structure of an allochthonous terrane containing early Palaeozoic island arc sequence. Journal of Asian Earth Sciences, 15: 453-464.
12. Gardner, C.J., Graham, I.T., Belousova, E., Booth, G.W., Greig, A., 2017. Evidence for Ordovician subduction–related magmatismin the Truong Son Terrane, SE Laos: implications for Gondwana evolution and porphyry Cu exploration potential in SE Asia. Gondwana Research, 44, 139–156
13. Golonka, J. 2007. Late Triassic and Early Jurassic paleogeography of the world. Palaeogeography, Palaeoclimatology, Palaeoecology, 244, 297–307.
14. Golonka, J. 2020. Late Devonian paleogeography in the framework of global plate tectonics. Global and Planetary Change, 86, 103129, https://doi.org/10.1016/j.gloplacha.2020.103129
15. Golonka, J., Embry, A., Krobicki, M., 2018. Late Triassic Global Plate Tectonics. In: Tanner L. (eds) The Late Triassic World. Topics in Geobiology, vol 46. Springer, Cham. pp 27-57.
16. Golonka, J., Hung, K.T., , Du, N.K., Krobicki, M., 2023. The eastern extension of the Avalonian terranes, the Prototethys and Paleotethys oceans. Geotourism, 20(1-2): 72-73.
17. Golonka, J., Krobicki, M., Pająk, J., Giang, N.V. & Zuchiewicz, W., 2006. Global plate tectonics and paleogeography of Southeast Asia. Faculty of Geology, Geophysics and Environmental Protection. AGH University of Science and Technology, Arkadia, Kraków, 1-128
18. Golonka, J., Krobicki, M., Słomka, T., Hung, K.T., Giang, N.V., 2018. The Indosinian orogeny in South-East Asia. Biuletyn AGH, 128-129, 14-16.
19. Hanski, E., Richard, J. W., Hannu, H., Polyakov, G.V., Pavel, A.B., Hoa, T.T. & Phuong, N.T., 2004. Origin of the Permian-Triassic komatiites, northwestern Vietnam. Contributions to Mineralogy and Petrology, 147, 453–469.
20. Hieu, P.T., 2017. The LA-ICP-MS U-Pb zircon age of riolite from the Dong Trau formation and its geological significances. Science & Technology Development, 5, 262–269.
21. Hieu, P.T., Chen, F.K., Thuy, N.T.B., Cuong, N.Q., and Li, S.Q., 2013. Geochemistry and zircon U-Pb ages and Hf isotopic compositions of Permian alkali granitoids of the Phan Si Pan Zone in northwestern Vietnam. Journal of Geodynamics, 69, 106–121.
22. Hieu, P.T., Li, S.Q., Yu, Y., Thanh, N.X., Le Tu, V., Siebel, W., and Chen, F., 2017. Stages of late Paleozoic to early Mesozoic magmatism in the Song Ma belt, NW Vietnam: evidence from zircon U–Pb geochronology and Hf isotope composition. International Journal of Earth Sciences, 106, 855–874.
23. Hieu, P.T., Son, L.M., Dung, L.T., Thanh, N.X., 2014. 470 Ma Gabbro-diabase in the Nui Nua area and its tectonic significance. Vietnam Journal of Geology, Series A, 340: 1-10 (in Vietnamese).

24. Hoa, T.T., Anh, T.T., Phuong, N.T., Dung, P.T., Anh, T.V., Andrey, E.I., Alexander, S.B., Lan, C.Y., Chung, S.L., Lo, C.H., 2008. Permo-Triassic intermediate–felsic magmatism of the Truong Son belt, eastern margin of Indochina. Comptes Rendus Geoscience, 340, 112–126.

25. Huang, W.M., Liu, X.J., Liu, L., Li, Z.L., Liu, X., Wu, H., 2023. Early Triassic roll-back of subducted Paleo-Tethys oceanic lithosphere: Insights from A2-type silicic igneous rocks in the Pingxiang area, southwest China. Geosphere, 19(X): 1-27, https://doi.org/10.1130/GES02617.1.

26. Hung, K.T., 2010. Overview of magmatism in northwestern Vietnam. Annales Societatis Geologorum Poloniae, 80 (2), 185-226.

27. Hutchison, C.S., 1989. Geological Evolution of Southeast Asia. Oxford Monographs on Geology and Geophysics, Oxford, UK, Clarendon Press, 376 pp.

28. Janvier, P., Thanh, T.D., Phuong, T.H., Truong, D.N., 1997. The Devonian vertebrates (Placodermi, Sarcopterygii) from central Vietnam and their bearing on the Devonian palaeogeography of Southeast Asia. Journal of Asian Earth Sciences, 15 (4–5), 393–406.

29. Janvier, P., Racheboeuf, P., Huu, H.N., Nhat, T.D., 2003. Devonian fish (Placodermi, Antiarcha) from Tra Ban Island (Bai Tu Long Bay, Quang Ninh Province, Vietnam) and the question of the age of the Do Son Formation. Journal of Asian Earth Sciences, 21 (7), 795–801

30. Jian, P., Liu, D.Y., Kröner, A., Zhang, Q., Wang, Y.Z., Sun, X.M., Zhang, W., 2009. Devonian to Permian plate tectonic cycle of the Paleo-Tethys Orogen in southwest China (II): insights from zircon ages of ophiolites, arc/back-arc assemblages and within-plate igneous rocks and generation of the Emeishan CFB province. Lithos 113, 767–784.

31. Krobicki, M., & Golonka, J., 2008. Emeishan volcanism of northwestern Vietnam and their connection with SE Asia palaeogeography and Permian/Triassic mass extinction event. Gondwana 13, Dali, China: 96-97 (in abstract).

32. Lan, C.Y., Chung, S.L., Shen, J.J., Lo, C.H., Wang, P.L., Hoa, T.T., Thanh, H.H., and Mertzman, S.A., 2000. Geochemical and Sr-Nd isotopic characteristics of granitic rocks from northern Vietnam. Journal of Asian Earth Sciences, 18, 267–280.

33. Leloup, P.H., Amaud, N., Lacassin, R., Kienast, J.R., Harrison, T.M., Trinh, P.T., Replumaz, A. & Tapponnier, P., 2001. New constraints on the structure, thermochronology, and timing of the Ailao Shan-Red River shear zone, SE Asia. Journal of Geophysical Research, 106 (B4), 6683-6732.

34. Leloup, P.H., Tapponnier, P., Lacassin, R., Searle, M.P., Dailai, Z., Xiaoshan, L., Langshang, Z., Shaocheng, J. & Trinh, P.T., 1995. The Ailao Shan-Red River shear zone (Yunnan, China). Tertiary transform boundary of Indochina. Tectonophysics, 251, 3-84.

35. Lepvrier, C., Maluski, H., 2008. The Triassic Indosinian orogeny in East Asia. C. R. Geoscience, 340, 75-82.

36. Lepvrier, C., Maluski, H., Van Vuong, N., Roques, D., Axente, V., and Rangin, C., 1997. Indosinian NW-trending shear zones within the Truong Son belt (Vietnam) 40Ar-39Ar Triassic ages and Cretaceous to Cenozoic overprints, Tectonophysics, 283, 105–127.

37. Lepvrier, C., Maluski, H., Vu, V.T., Leyreloup, A., Phan, T.T., and Nguyen, V.V., 2004. The early Triassic Indosinian orogeny in Vietnam (Truong Son Belt and Kontum massif): implication for the geodynamic evolution of Indochina, Tectonophysics, 393, 87–118.

38. Li, Q., Lin, W., Wang, Y., Faure, M., Meng, L., Wang, H., ... & Van Vu, T., 2021. Detrital zircon UPb age distributions and Hf isotopic constraints of the Ailaoshan-Song Ma Suture Zone and their paleogeographic implications for the Eastern Paleo-Tethys evolution. Earth-Science Reviews, 221, 103789. https://doi.org/10.1016/j.earscirev.2021.103789.

39. Lin, W., Wang, Y., Liu, F., Meng, L.T., Ji, W.B., Wei, W., Chu, Y., Song, C., Wu, Q.Y., 2022. Matrix of the ophiolitic mélange zone and its tectonic implications: Insights of the eastern Paleo-Tethys. Acta Geol. Sin. 96 (10), 3449–3467 (in Chinese with English abstract).

40. Liu, F., Lin, W., Wang, Y., Meng, L., Faure, M., Vuong, N.V., Wu, Q., Chu, Y., Wei, W., Hoai, L.T.T., Tich, V.V., Li, Q., Wang, H. & Chen, K., 2023. Heterogeneity of the Ailaoshan–Song Ma ophiolitic mélange and its palaeogeographic implications for the evolution of Eastern Palaeo-Tethys. Tectonophysics, 858, 229848.

41. Maluski, H., Lepvrier, C., Jolivet, L., Carter, A., Roques, D., Beyssac, O., Ta Trong Tang, Nguyen Duc Thang, Avigad D., 2001. Ar–Ar and fission -track ages in the Song Chay Massif: Early Triassic and Cenozoic tectonics in Northern Vietnam, Journal of Asian Earth Sciences, 19, 233-248

42. Maluski, H., Lepvrier, C., Layreloup, A., Vu Van Tich, Phan Truong Thi, 2005. 40Ar-39Ar geochronology of the charnokites and granulites of the Kan Nack Complex, Kon Tun Massif, Vietnam. Journal of Asian Earth Sciences, 25, 653-677.

43. Meng, L., Li, Z.X., Chen, H., Li, X.H., Zhu, C., 2015. Detrital zircon U-Pb geochronology, Hf isotopes and geochemistry constraints on crustal growth and Mesozoic tectonics of southeastern China. J. Asian Earth Sci. 105, 286–299.

44. Metcalfe, I., 1994. Late Paleozoic and Mesozoic Paleogeography of Eastern Pangea and Tethys. In: Embry, A. F., Beauchamp, B., Glass, D. J. (Eds.), Pangea: Global environment and resources. Canadian Society of Petroleum Geologists Memoir, 17, 97-111.

45. Metcalfe, I., 1996. Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys, In: Li, Z.X., Metcalfe, I., Powell, C.M, (eds.), Breakup of Rodinia and Gondwanaland and assembly of Asia. Australian Journal of Earth Sciences, 43, 605-623.

46. Metcalfe, I., 1998. Biogeography and Geological Evolution of SE Asia. Backhuys Publishers: Netherlands; 25–41.

47. Metcalfe, I., 2011. Paleozoic-Mesozoic history of SE Asia. Geological Society Special Publication, 355, 7-35.

48. Metcalfe, I., 2021. Multiple Tethyan ocean basins and orogenic belts in Asia, Gondwana Research, 100, 87-130.

49. Nam, T.N., 1998. Thermotectonic events from Early Proterozoic to Miocene in the Indochina craton: implication of K±Ar ages in Vietnam. Journal of Asian Earth Sciences, 16, 475-484.

50. Nguyen, V.N., Hoang, Q.C., Ha, X.B., Le, D.N., Nguyen, T.B.T., Dao, D.T., 2005. U–Pb Zircon Age of Granitoids of the Huoi Tong Complex. Department of Geology and Mineral Resources of Vietnam, Hanoi, pp. 164–170 (in Vietnamese).

51. Shouxin, Z. & Yongyi, Z., 1991. The geology of China. In: Moullade, M. & Nairn, A. E. M. (eds),The Palaeozoic. A The Phanerozoic Geology of the WorldI. Elsevier, Amsterdam: 219-274

52. Son, P. (ed.), Thuc, D.D., Thang, N.D. & Ty, T.V., 1974 (compiled), 1978 (revised). Geological map of Vietnam at 1:200,000 scale. Son La sheet, with the explanatory note "Geology of the Son La sheet". Geological Department of Vietnam, Ha Noi, 118 pp.

53. Thanh, T.D., Janvier, P., Phuong, T.H., 1996. Fish suggest continental connections between Indochina and South China Blocks in Middle Devonian time. Geology 24 (6), 571–574

54. Thanh, N.X., Santosh, M., Hai, T.T., Hieu, T.P., 2015. Subduction initiation of Indochina and South China blocks: insight from the forearc ophiolitic peridotites of the Song Ma Suture Zone in Vietnam. Geological journal, 51(3): 421-442.

55. Thanh, T.V., Hieu, P.T., Minh, P., Nhuan, D.V. & Thuy, N.T.B., 2019. Late Permian-Triassic granitic rocks of Vietnam: the Muong Lat example. International Geology Review, 61:15, 1823-1841, DOI: 10.1080/00206814.2018.1561335.

56. Tran, H.T., Zaw, K., Halpin, J.A., Manaka, T., Meffre, S., Lai, C.K., Lee, Y., Le, H.V., Dinh, S., 2014. The Tam Ky-Phuoc Son Shear Zone in central Vietnam: tectonic and metallogenic implications. Gondwana Res. 26, 144–164.

57. Tran, T.V., Faure, M., Nguyen, V.V., Bui, H.H., Fyhn, M.B.W., Nguyen, Q.T., Lepvrier, C., Thomsen, T.B., Tani, K., Charusiri, P., 2020. Neoproterozoic to early Triassic tectono–stratigraphic evolution of Indochina and adjacent areas: a review with new data. Journal of Asian Earth Sciences, 191, 104231

58. Tri, T.V. (ed.), 1979 (1977 in Vietnamese). Geology of Vietnam, (the North part). Explanatory note to the geological map on 1:1,000,000 scales. Ha Noi, Science and Technology. Publishing House, 354 pp. (In Vietnamese), 78 pp. (In English).

59. Tri, T.V. & Khuc, V. (ed.), 2011. Geology and Earth Resources of Vietnam. General Department of Geology and Minerals of Vietnam. Publishing House for Science and Technology, Hanoi.

60. Trung, N.M., Nuong, N.D. & Itaya, T., 2007. Rb-Sr Isochron and K-Ar ages of igneous rocks from the Sam Nua Depression Zone in Northern Vietnam. Journal of Mineralogical and Petrological Sciences, 102: 86-92

61. Truong, P.D. (ed), 1999. Report on geological and mineral resources in the Son La sheet group at scale of 1:50,000. General Department of Geology and Minerals of Vietnam (in Vietnamese).

62. Tung, N.X. & Tri, T.V., 1992. The geologic formations and dynamics of Vietnam. Institute of Geology and Mineral resources of Vietnam, Ha Noi, 269 pp (in Vietnamese).

63. Wang, Y., Zhang, Y., Qian, X., Wang, Y., Cawood, P.A., Gan, C., Senebouttalath, V., 2021. Early Paleozoic accretionary orogenesis in the northeastern Indochina and implications for the paleogeography of East Gondwana: constraints from igneous and sedimentary rocks. Lithos, 382–383, 105921, https://doi.org/10.1016/j.lithos.2020.105921.

64. Xu, X., Liang, C., Chen, J., Xu, Y., 2021. Provenance analysis of Jurassic basins along Chaling-Chenzhou-Linwu Fault, South China: implications for palaeogeographic reconstruction and Mesozoic tectonic transition. Geol. J. 56 (5), 2656–2675.

65. Xu, X., 2023. Late Triassic to Middle Jurassic tectonic evolution of the South China Block: Geodynamic transition from the Paleo-Tethys to the Paleo-Pacific regimes, Earth-Science Reviews, https://doi.org/10.1016/j.earscirev.2023.104404

66. Zhang, R.Y., Lo, C.H., Chung, S.L., Grove, M., Omori, S., Hzuka, Y., Liou, J.G., Tri, T.V., 2013. Origin and Tectonic Implication of Ophiolite and Eclogite in theSong Ma Suture Zone between the South China and IndochinaBlocks. Journal of Metamorphic Geology, 31, 49–62. https://doi:10.1111/jmg.12012