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Neoproterozoic to Early Triassic tectono-stratigraphic evolution of Indochina and adjacent areas: a review with new data

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Abstract

The Neoproterozoic to Early Triassic tectono-stratigraphic evolution of Indochina and adjacent areas can be divided into six mega-episodes: 1) The Neoproterozoic-Early Cambrian mega-episode was characterized by shallow marine environment in the Sino-Vietnam composite terrane. Meanwhile, the different blocks of the Indochina composite terranes were still separated by branches of the Proto-Tethys. Sino-Vietnam and part of Indochina amalgamated along the Proto-Song Ma suture by the end of the Early Cambrian. 2) During the Middle Cambrian-Early Ordovician mega-episode, shallow shelf carbonate deposition prevailed north of the Proto-Song Ma suture with associated strata containing a rich benthic fauna. This contrasts with deep marine and volcanic arc setting in the south of the Proto-Song Ma suture. 3) The Middle Ordovician-Silurian mega-episode was characterized by subduction of the Tam Ky-Phuoc Son Ocean beneath the Viet-Lao terrane in the north and the Kon Tum terrane in the south. This was followed by a collisional orogeny that sutured the Kon Tum terrane with the Viet-Lao and Viet-Cambodia terranes along the Tam Ky-Phuoc Son suture. The hypothetical Po Ko and Chu Sinh sutures are discussed. The collision led to an intra-continental orogeny in the Sino-Vietnam composite terrane. By the end of the mega-episode, a unified Sino-Vietnam-Indochina super-terrane was established. During the latest Silurian-Early Devonian, benthic fauna and flora of the Sino-Vietnam and Indochina composite terranes shared Cathaysian affinity. 4) The Devonian-Tournaisian mega-episode was characterized by an Early-Middle Devonian transgression and a Late Devonian-Earliest Carboniferous regression, except for parts of northern Indochina where deep marine conditions remained. 5) During the Viséan-Middle Permian, the Song Ma ocean reopened in the north of Indochina. Meanwhile in the west, a volcano-plutonic belt formed due to eastward subduction of the Paleo-Tethys under the Indochina composite terrane. 6) The Late Permian-Early Triassic mega-

episode was characterized by Emeishan mantle plume related continental rifting, and the Indosinian orogeny resulting from resuturing of the Indochina and Sino-Vietnam composite terranes along the Song Ma suture.

1. Introduction

Indochina constitutes the core of Southeast Asia (Figure 1). It is composed of Gondwana derived crustal fragments that are amalgamated throughout the Neoproterozoic to Early Mesozoic time (Carter et al., 2001; Faure et al., 2014; Fromaget, 1941; Lepvrier et al., 2008; Metcalfe, 2013, 2017). However, Late Paleozoic to Cenozoic tectonism, magmatism and basin development have overprinted and concealed many of the older structures (Faure et al., 2018; Fyhn et al., 2018; Hoang and Flower, 1998; Leloup et al., 2001; Phan and Hoang, 2008; Tapponnier et al., 1990; Tran et al., 2014), and the Neoproterozoic to Early Triassic evolution remains poorly understood.

The extensive Paleozoic and Mesozoic rocks in Vietnam provide a detailed documentation of the paleontological, stratigraphic, igneous, and metamorphic development critical to unravelling the tectonostratigraphic evolution of Indochina and surrounding Southeast Asia (Tran and Nguyen, 1988; Tran and Vu, 2011). This paper integrates existing syntheses of the Neoproterozoic to Early Triassic geologic evolution (Bunopas, 1994; Burrett et al., 2014; Dovjikov, 1965; Faure et al., 2014; Gatinsky and Hutchison, 1986; Hutchison, 2007; Khin Zaw et al., 2014; Lepvrier et al., 2008; Metcalfe, 2013; Ridd et al., 2011; Tong and Vu, 2011; Tran and Vu, 2011; Wongwanich and Burrett, 1983) with recent studies on magmatic and metamorphic dating, detrital zircon analysis, and new paleontological, stratigraphic, structural and tectonic investigations in Vietnam and surrounding areas published both internationally and in native language bulletins (Bercovici et al., 2012; Faure et al., 2018;

Nguyen X. B. et al., 2015; Usuki et al., 2013; Vu et al., 2000). The presented review is complemented with unpublished radiometric age data from fieldwork in Vietnam, Cambodia and Laos. The integration with the new data sheds light on the Neoproterozoic through Early Triassic stratigraphic and tectonic evolution of Indochina and a revised model for the establishment of Indochina is proposed.

2. Geological setting and tectonic framework of Indochina and adjacent areas

Indochina and the adjacent areas consist mainly of continental fragments, orogenic belts, rifted terranes, and obducted oceanic crusts of different ages of formation and amalgamation. Some of them also experienced polyorogenic reworking. These continental blocks derived from Gondwana during the opening and closure of Proto-Tethyan, Paleotethyan and Tethyan oceans (Burrett et al., 1990, 2014; Metcalfe, 2013, 2017), presently identified as suture zones. These units are the Sino-Vietnam composite terrane (also referred to as the “South China block”), the Indochina composite terrane, and the Sibumasu composite terrane (Figure 1).

2.1. Sino-Vietnam composite terrane

The Sino-Vietnam composite terrane consists of the South China region, the northern part of the Hainan Island and part of north Vietnam. It is bounded to the north by the Qinling-Dabie suture, to the southwest by the Ailaoshan-Song Ma Suture, to the south by the Song Chay-Hainan suture, and its possible eastward extension is concealed underneath the East Vietnam Shelf (Figure 1; Faure et al., 2016). It may be further divided into the Yangtze block and the Cathaysia block, separated by the Neoproterozoic Jiangshan-Shaoxing fault (Charvet, 2013; Faure et al., 2009; Xu et al., 2016). These two blocks were welded together in the Neoproterozoic during the Jiangnan Orogeny (865-820 Ma) (Charvet, 2013; Ren et al., 2013; Shu et al., 2015, Yan et al., 2019).

In northern Vietnam, the exposed Precambrian basement is attributed to the Hoang Lien Son-Ailaoshan metamorphic terrane (Figure 1). This terrane yields zircon U-Pb SHRIMP ages of 2936 Ma, 2362 Ma, 1800 Ma, 838 Ma and 760 Ma (Tran et al., 2003). Significant Cenozoic left-lateral strike-slip faulting along the Red River shear zone has displaced the North West Vietnam domain to the SE relative to North East Vietnam domain (Figure 1; Leloup et al., 2007; Tapponnier et al., 1990).

2.2. Indochina composite terrane

Earlier French geologists used the term “Indosinia” to indicate a large region including much of Vietnam, Laos, Cambodia and the adjacent East Vietnam Shelf (Fromaget, 1941, 1952; Hoffet, 1933; Phan, 1995; Ren et al., 2013; Saurin, 1935). In this paper, the term Indochina composite terrane includes the reworked Precambrian metamorphosed terranes of Phu Hoat, Kon Tum and possibly Pailin, as well as Paleozoic terranes of Viet-Lao, Viet-Cambodia, Loei-Phetchabun, Simao, Sukhothai and East Malaysia (Figure 1). This concept is similar to the “large Indochina terrane” of Burrett et al. (2014). This composite terrane is bounded to the north by the Ailaoshan-Song Ma suture, to the west by the Chiang Rai Line (Sone and Metcalfe, 2008, Wang et al., 2018) that extends southward to the Sra Kaeo suture (Hada, 1999; Wakita and Metcalfe, 2005) and then to the Bentong-Raub suture in East Malaysia (Metcalfé, 2013, 2017). Its eastern boundary is concealed underneath the East Vietnam Shelf.

Several terranes are distinguished within the Indochina block (Figure 1). The Viet-Lao and Viet-Cambodia terranes are composed of folded fossiliferous Paleozoic sediments and igneous rocks. The name Viet-Lao terrane was first used by Gatinsky et al. (1970) and for its most part coincides with the Truong Son terrane used by other authors (Burrett et al., 2014; Lepvrier et al., 2008). The Viet-Cambodia terrane was first established by Faure et al. (2018), and covers southern Vietnam, most of Cambodia and eastern Thailand. The Paleozoic and older rocks in this terrane are mostly covered by Mesozoic strata. The Kon Tum terrane underwent

polycyclic high grade metamorphism including at least an Early Paleozoic and a Late Permian-Early Triassic event (Faure et al., 2018; Nakano et al., 2007, 2013; Osanai, 2004; Osanai et al., 2008; Owada et al., 2016, 2006; Roger et al., 2007; Usuki et al., 2009, 2013; Vu et al., 2013). The Loei-Phetchabun terrane is composed of Late Ordovician-Triassic sequences deposited in both shallow and deep marine environment (Department of Mineral Resources, 2014). The Sukhothai terrane is mostly composed of Late Paleozoic and Early Mesozoic volcanogenic and arc volcanic sequences. The Simao terrane consists of Paleozoic volcanoclastic sedimentary sequences ranging from Silurian to Permian in age, which are truncated by a Late Triassic unconformity (Wang et al., 2014).

2.3. Sibumasu composite terrane

The Sibumasu composite terrane extends from northeast Sumatra, west Malaysia, through west Thailand, Myanmar, and west Yunnan (Figure 1; Barber et al., 2011). The Paleozoic sequence of the Sibumasu composite terrane is floored by Upper Cambrian-Lower Ordovician shallow marine siliciclastic rocks that progressively change upward into Silurian-Devonian deep marine fine-grained sediments bearing graptolite and tentaculate. The Carboniferous deposits change from dominantly shallow marine limestone in Baoshan to radiolarian deep-water siliciclastics in NW Malaysia and southern Thailand (Burrett et al., 2016). Early Permian diamictites were deposited, followed by Middle-Late Permian platform carbonate (Burrett et al., 2014; Metcalfe, 2013).

2.4. Suture zones

2.4.1. Song Ma suture

The NW-SE striking Song Ma zone separates the Sino-Vietnam (S. China) composite terrane to the north from the Indochina composite terrane to the south (Figure 1). It contains ultramafic and mafic mélangé assemblages and was documented by French geologists

(Fromaget, 1941, 1952; Jacob, 1921) under the name of “Thanh Hoa cicatrice.” It was recognized later as an ophiolitic suture between the Indochina and Sino-Vietnam composite terranes (Dao and Huynh, 1995, p. 64; Hutchison, 1989, 2007; Ngo and Nguyen, 2016; Tran et al., 1977; Tran and Vu, 2011; Zhang et al., 2013, 2014). The suturing age and subduction polarity remains controversial. There are two main lines of evidence for the age of suturing. Some authors consider the suturing to have occurred between the Silurian and the Devonian (Findlay, 1997; Hutchison, 1989). This view is supported by paleontological evidence (Janvier et al., 1997, 2003; Tong et al., 1996). Most authors favored a Triassic collision prior to the upper Triassic unconformity (Faure et al., 2014; Lepvrier et al., 2004, 2008; Şengör et al., 1988; Tran, 1979). This view is supported by the age of high-pressure metamorphism recorded along the Song Ma suture. Lepvrier et al. (1997, 2004, 2008) first documented ^{40}Ar - ^{39}Ar ages of 250-245 Ma reflecting shearing along the Song Ma suture zone. Nakano et al. (2008) showed a monazite U-Th-Pb age of 213 ± 5 Ma for a pelitic gneiss associated with high pressure mafic granulite for this suture zone. Zircon U-Pb SHRIMP dating of Song Ma eclogite yields a similar age of 230.5 ± 8.2 Ma (Zhang et al., 2013) and U-Pb SHRIMP ages of ultramafic and mafic rocks range from 340 Ma to 310 Ma, corresponding to the oceanic crust formation period (Zhang et al., 2014). Based on the Sm-Nd and U-Pb isotopic ages of ophiolitic rocks ranging from 387 to 313 Ma, Nguyen V.V. et al. (2013) suggested that oceanic crust formed during the Carboniferous, followed by Late Permian-Early Triassic continental collision between the Indochina and the Sino-Vietnam composite terranes.

2.4.2. Song Chay suture

The Song Chay suture was first proposed by Pusharovsky (1965) and Gatinsky et al. (1970). Along the Song Chay fault, an ophiolitic mélange consists of sporadically exposed blocks of serpentized ultramafic and mafic bodies, Lower Paleozoic limestone, chert and siliceous mudstone enclosed in a sandstone-mudstone matrix (Faure et al., 2014; Lepvrier et

al., 2011). The age of the matrix is unknown, but cannot be younger than Early Neogene as conglomerate of this age unconformably covers the Song Chay ophiolitic mélange (Lepvrier et al., 2011). The Song Chay suture was previously interpreted as a segment of the Ailaoshan-Song Chay-Song Ma suture laterally displaced by Cenozoic strike-slip tectonics (Faure et al., 2014, 2016, 2018).

2.4.3. Tam Ky-Phuoc Son suture

The E-W striking Tam Ky–Phuoc Son suture consists of metapelite, metapsammite, and paragneiss of Kham Duc and Nui Vu complexes, and metagabbro, amphibolite, serpentinized ultramafic with ophiolitic geochemical affinity (Izokh et al., 2006; Tran et al., 2004; Tran, 1979; Tran and Vu, 2011). It is intersected by the Po Ko suture to the west, but its possible extension in Laos is not clearly defined. The Tam Ky-Phuoc Son suture has been argued to extend to the NW in Laos and merge with the Thakhek-Da Nang fault (Figure 1; Shi et al., 2015; Thassanapak et al., 2018). The exposure of ultramafic bodies, including harzburgite and dunite, along the Da Krong shear zone in Quang Tri province (Nguyen V.T., 1996), as well as a small mafic and ultramafic body in B. Bor, Borikhan district in Laos may lend credence to this argument. The suture zone is considered to represent either an Early Paleozoic ocean separating the Viet-Lao terrane in the north from the high grade metamorphic Kon Tum terrane in the south (Lepvrier et al., 2004; Tran, 1979) or a product of the Indosinian orogeny (Gatinsky and Hutchison, 1986).

Detrital zircon U-Pb ages of 550 Ma from metasandstones from the Kham Duc complex (Usuki et al., 2009), and magmatic zircon ages of 518 Ma and 502 Ma for a trondhjemite–tonalite suite (Nguyen et al., 2019) reveal the existence of a Late Neoproterozoic to Early Cambrian Proto-Tethyan ocean between the Viet-Lao terrane and a continental basement preserved as block enclosed in migmatite in the Kon Tum terrane. This complex experienced a poly-cyclic metamorphism during the Early Paleozoic and the Late Permian–Early Triassic. The Early Paleozoic metamorphic evolution is characterized by a HP to MP-LT event, and

subsequently a LP-HT event with a T climax at ca. 450 Ma (Usuki et al., 2009), followed by ca. 430 Ma magmatism (Tran et al., 2014). The Late Permian-Early Triassic event, which is also characterized by HT (even UHT) conditions, took place between 250 and 236 Ma (Lepvrier et al., 2004, 2008) in a retrograde decompression setting (Nakano et al., 2013; Osanai et al., 2008). More recently Faure et al. (2018) and Owada et al. (2016) argued that the HT metamorphism represented an intraplate event.

2.4.4. Po Ko suture

The Po Ko suture strikes N-S along the western margin of the Kon Tum terrane (Figure 1). Ultramafic rocks of the Plei Weik complex occur in the Po Y area within the Neoproterozoic to Early Paleozoic rocks (Lepvrier et al., 2008; Tran, 1998). Banded and serpentized dunite-wehrlite-clinopyroxenite-gabbro complexes typical of ophiolitic assemblage also crop out in this area and extend into southeast Laos and northeast Cambodia (Ha et al., 2009; Tran and Vu, 2011). Ultramafic and mafic rocks in the Po Y area have N-MORB affinity, and zircon U-Pb LA-ICP-MS age of 459.5 ± 4.3 Ma (Bui An Nien, personal communication). About 50 km west of the Po Ko fault in Laos, diorite and rhyolitic rocks were mapped in the Donken area (Figure 1) with whole-rock geochemistry compatible with an island arc setting. These rocks are dated as 477-470 Ma (Early Ordovician) using zircon U-Pb Q-ICP-MS (Gardner et al., 2017). Gardner et al. (2017) interpreted their occurrence to be associated with bivergent subduction of the Tam Ky Phuoc Son ocean under both the Kon Tum terrane and the Viet-Lao terrane.

2.4.5. Chu Sinh suture

To the southeast of the Kon Tum terrane, a tectonic mélangé composed of metabasalt, metagabbro, serpentized peridotite, metachert, marble, metagraywacke and metapelite is exposed in a narrow E-W and NW-trending zone south of the Ea Knop town (Figure 1; Nguyen, 1998). It is interpreted as the Chu Sinh suture also referred to as the Ea Kar-Ea Drang suture in Vietnamese literature (Nguyen X. B. et al., 2015). Amphibolite of the complex yield a Sm-Nd

age of 477 ± 42 Ma (Nguyen X.B. et al., 2015). This suture is not mentioned in the international geologic literature and requires further investigations.

3. Review of published data for Indochina and adjacent areas

In this section, we review the tectono-stratigraphic data of the Sino-Vietnam (South China) and Indochina composite terranes, chronologically ordered into six mega-episodes. For the Sino-Vietnam composite terrane, we focus on the north Vietnam region, with correlations to the southern part of South China.

3.1. Neoproterozoic - Early Cambrian mega-episode

In the Neoproterozoic, Indochina and Sino-Vietnam consisted of multiple terranes separated by branches of the Proto-Tethys ocean (see section 2). The Late Neoproterozoic-Early Cambrian sediments in Indochina and adjacent areas are mainly composed of pelitic-mafic volcanic sequences in the lower part and carbonates in the upper part (Figure 2). They unconformably overlie the plutonic-metamorphic basement dated as 755 Ma (Tran, 2003; Tran and Vu, 2011). An Early Ediacaran age is assigned to this unconformity.

3.1.1. Sino-Vietnam composite terrane

North of the Hoang Lien Son-Ailaoshan terrane (Figure 1), the stratigraphy is composed of siliciclastics and dolomite of the Da Dinh Fm. (NP) and siliciclastics, carbonates and phosphatic sediments of the Cam Duong Fm. (ϵ_1) (Figure 3). The Cam Duong Fm. contains oncolite fossils such as *Medularites dineolatus* and *Ambigolamellatus horridus*, as well as acritarchs such as *Archaeohystrichosphaeridium* and *Barlinella* (Pham, 2008). These deposits are distributed in the NW-SE trending Lao Cai phosphate bearing basin, stretching for hundreds of kilometers and unconformably overlying the Hoang Lien Son-Ailaoshan Precambrian basement. They can be correlated to the Dengying Fm. and Meishucun Fm., respectively, in Yunnan, China (China Geological Survey, 2004; Tran and Vu, 2011).

Along the Song Ma suture zone, the Nam Co Fm. (Figure 1) consists of metasediments and metapelite interbedded with thin layers of metabasalt and occasionally with marbles. The formation contains Late Neoproterozoic-Early Cambrian acritarchs and is unconformably overlain by the Middle Cambrian Song Ma Fm. (Tran and Vu, 2011). Detrital zircon U-Pb ages of 850-736 Ma from the Nam Co formation provide a lower bound for its depositional age being younger than the Early Neoproterozoic (Bui V. H. et al., 2018).

In northern Vietnam, the Po Sen complex, distributed in the Hoang Lien Son-Ailaoshan terrane, consists of I-type granodiorite-granite and orthogneiss with typical calc-alkaline affinity, yielding zircon U-Pb SHRIMP ages of 751 ± 7 Ma (Tran, 2003; Wang et al., 2011). The Song Chay-Dulong orthogneiss is coeval with the Po Sen granite and yields zircon U-Pb SHRIMP ages of 799-761 Ma (Liu et al., 2006; Yan et al., 2006).

3.1.2. Indochina composite terrane

Phu Hoat terrane

The Phu Hoat terrane (Figure 1), considered as a Late Neoproterozoic-Early Paleozoic microcontinent, consists of gneiss and amphibolite of the Nam Su Lu complex, and gneiss, micaschist, and migmatites of the Bu Khang complex. The Bu Khang complex yields inherited zircon ages from 2540 to 600 Ma (Carter et al., 2001). The S-type granite of the Nam Gai complex with a zircon U-Pb SHRIMP age of 783 ± 12 Ma is considered an anatectic product of the Bu Khang complex (Nguyen C.D. et al., 2015). Both the Bu Khang and the Nam Gai complexes are strongly affected by Indosinian tectonics as documented by granitic intrusions and metamorphism dated at 249 ± 5 Ma (Nguyen C.D. et al., 2015).

The Neoproterozoic-Early Cambrian volcano-sedimentary deposits show a clear transition from south to north. To the south, the Kham Duc complex consists of 2600 m thick of greenschists and tholeiitic basalt interbedded with quartzite, siliceous shale, and bedded

limestone. To the north, the Suoi Mai Fm. consists of fine grained quartzite interbedded with biotite-chlorite phyllite that overlies the Bu Khang complex across a possible unconformity.

Kon Tum terrane

The amphibolite to greenschist facies metamorphic rocks of the Kon Tum terrane are attributed to the Late Neoproterozoic-Early Cambrian Nui Vu complex. They were derived from organic-rich claystone, chert, as well as andesitic basalt and calc-alkaline effusive protoliths (Figure 2; Tran and Vu, 2011, p. 398). Enclosed in the Nui Vu complex, blocks of metamorphosed mafic-ultramafic rocks, 518-502 Ma trondhjemite-tonalite (Nguyen et al., 2019), chert and marble belonging to the Hiep Duc ophiolite assemblage form a tectonic mélange. Metagabbro of the Phu My complex and inherited zircon from Kan Nack complex yielded ages of 678 ± 23 Ma (Osanai, 2004) and 1404 Ma (Nam et al 2001), respectively.

Pailin terrane

In western Cambodia and southeast Thailand, the Pailin terrane consists of mylonitized quartzo-feldspathic gneisses, amphibolites, and migmatites exposed in a ca. 40 km-long SE-trending belt (Figure 1; Gubler, 1935; Kun and Say, 1986). However, the significance of this terrane is still poorly understood.

3.2. Middle Cambrian-Early Ordovician mega-episode

Middle Cambrian - Early Ordovician sequences were deposited on the Yangtze-Hoang Lien Son-Ailaoshan, the Viet-Lao, the Viet-Cambodia terranes, and the Sibumasu composite terrane over the early Middle Cambrian unconformity. These series are composed of terrigenous and carbonate sediments deposited on a continental shelf (Figure 2).

3.2.1. Sino-Vietnam composite terrane

North East Vietnam

In the North East Vietnam domain, the Middle Cambrian-Early Ordovician sequence includes the Ha Giang, Chang Pung and Lutxia Fms. to the NW and the Than Sa Fm. to the SE (Figure 3). The Middle Cambrian Ha Giang Fm. is composed of terrigenous sediments with carbonate interbeds (Figure 4A). The formation is rich in fossils such as trilobites (Figure 5) and brachiopods (Pham, 2008, pp. 21–26; Tran and Vu, 2011, p. 54), representing shallow marine fauna that closely resembles Early Paleozoic marine fauna in South China (Tong and Vu, 2011, pp. 9-10). In addition, the Ha Giang Fm. also includes interbeds of metabasalt, meta-andesite and porphyroid, which are exposed around the periphery of the Song Chay massif. Geochemical analysis suggests that these interbeds represent intra-plate basalts (Tran and Vu, 2011, pp. 226 & 398). Further up section, the Late Cambrian Chang Pung Fm. (Figure 4B) and Early Ordovician Lutxia Fm. (Figure 3) are composed of carbonates interbedded with argillaceous shale, siltstone and sandstone containing abundant shallow marine trilobites and brachiopods (Chang Pung Fm.: *Blackwelderia-Paralorenzella*, *Chuangia*, *Irvingella*, *Billingsella tonkiniana*, *Prosaukia*, *Calvinella*; Lutxia Fm.: *Isotelus stenocephalus*, *Pseudokainella* sp.) (Pham, 2008, pp. 104–106). Enclosed within the Ha Giang Fm. are the Nam But ultramafic complex, Bach Sa gabbroid and 470 Ma Thanh Long plagiogranite (Bui, 2010, p. 119).

To the SE of North East Vietnam, the rhythmic terrigenous sediments of the Middle Cambrian-Early Ordovician Than Sa Fm. contain agnostid trilobites, including the Cambrian *Lotagnostus-Agonostus* zone and *Hedinaspis-Charchaquia-Niobella* beds in the lower part (Pham, 2008, pp. 123–126). The deposits grade upward into Tremadocian black shale bearing graptolite such as *Tetragraptus aqproximatus* N., *T.acclinans*, *Expansograptus constrictus* (Rushton et al., 2018). The fauna could be the correlative of that in the Huangdongkou Fm in

the Jiangnan belt in South China (Figure 1). Such fauna assemblages are indicative of a relatively deep depositional environment and suggests an interconnection with the Jiangnan-Chukiang (South China) and NE Australia basins (Shergold, 1995).

North West Vietnam

In the North West Vietnam domain, the Middle Cambrian-Early Ordovician sequence, including the Song Ma, Ham Rong and Dong Son Fms., are exposed on the NE side of the Ma River (Figures. 2&3). Lying unconformably on the Nam Co Fm., the Middle Cambrian Song Ma Fm. has a consistent thickness of about 650 m and consists of a basal conglomerate (30 m thick) that transitions upward to quartz-sericite schist, metabasalt, black shale and calcareous shale. The formation yields brachiopods such as *Lingulella* sp., *Obolus* sp., and trilobites such as *Solenoparia* sp., *Cyclolorenzella* cf. *Parabola*, *Anomocarina?* sp., *Pseudagnostus douvillei*. Further up section, the Late Cambrian-Early Ordovician Ham Rong Fm. consists of oolitic dolomitic limestone interbedded with marly shale and sandstone that contain abundant trilobites (*Dreparura premesnili*, *Damesella brevicaudata*, *Calvinella walcotti*) and brachiopods (*Billingsella tonkinesis*) (Pham, 2008, pp. 107–115). They grade upward into terrigenous coarse-grained sediments of the Early Ordovician Dong Son Fm., bearing trilobites such as *Asaphopsis jacobi*, *Asaphellus trinodosus*, and *Annamitella asiatica* (Dovjikov, 1965, pp. 169–170). These Middle Cambrian to Early Ordovician fauna suggests a continental shelf setting (Pham, 2008). Situated farther to the NE, along the Da River, the Ben Khe Fm. (Figures. 2&3) consists of flyschoid terrigenous sediments with calcareous shale interbeds (Tran and Vu, 2011, p. 57).

3.2.2. Indochina composite terrane

To the north and west of the Kon Tum terrane, the Viet-Lao and Viet-Cambodia terranes contain terrigenous-volcanogenic sediments of the A Vuong Fm. It rests unconformably on the

Kham Duc and Nui Vu complexes and is unconformably overlain by the Long Dai Fm. (Figures. 2&3). The formation consists of quartz-muscovite-sericite schist, siliceous schist, felsic effusive, banded dolomitic marble, actinolite-epidote schist and black shale (Nguyen, 1995, 1997; Tran, 1998). The black shale contains Tremadocian (Early Ordovician) planolites and graptolites (*Acanthograptus sinensis*, *A. macilentus*, *Dictyonema asiaticum*) (Nguyen, 1995, 1997; Pham, 2008, p. 131). Further southwest, in Stung Treng (northeast Cambodia), Middle Cambrian-Early Ordovician quartzitic sandstone and calcareous siltstone contain trilobites such as *Asaphiscus* aff. *Gregarious* (= *Balainia* aff. *gregaria*) (Pham, 2008; Saurin, 1935, 1956).

Within the Kon Tum terrane, low grade metamorphosed volcano-terrigenous deposits of black shale, black cherty shale and quartzitic sandstones interbedded with dolomitic limestone, porphyritic andesite, metabasalt and metarhyolite are attributed to the Middle Cambrian-Early Ordovician Phong Hanh Fm. (Tran, 1998, Tran and Vu, 2011, p.60). The formation rests unconformably on supposed Neoproterozoic metamorphics, which are intruded by 470-418 Ma granodiorite of Dien Binh Complex. Fossiliferous Devonian sediments cover the Phong Hanh Fm. (Figure 2).

3.3. Middle Ordovician-Silurian mega-episode

This mega-episode is characterized stratigraphically by flyschoid and volcano-clastic sedimentation in both the Sino-Vietnam and Indochina composite terranes. These deposits unconformably overlie the Middle Cambrian-Early Ordovician rocks (Tran and Vu, 2011).

3.3.1. Sino-Vietnam composite terrane

In the Cathaysia and Yangtze blocks in both South China and north Vietnam, the Late Ordovician stratigraphic records indicate a shallowing upward of the sedimentary facies, changing from deep-marine graptolitic shales to shallow-water, coarse grained clastic rocks

(Shu et al., 2015; Tran and Vu., 2011). These deposits are capped by an Early Devonian angular unconformity. In South China, Silurian deposits are only found in the Qin-Fang region (Figure 1) where more than 9 km of Silurian-Early Devonian siliciclastic rocks are overlain unconformably by Middle Devonian deposits (Zhang et al., 2018).

North East Vietnam

In North East Vietnam, a similar paleo-environment pattern to that of South China occurred during the Late Ordovician-Early Silurian. In the Thai Nguyen province, the Middle-Late Ordovician Na Mo Fm. consists of neritic sandstone, shale, and siltstone containing trilobites such as *Remopleurides taliangensis*, *Synhomalonotus birmanicus* and coral such as *Plasmoporella* sp. Conformably overlying the Na Mo Fm., the Phu Ngu Fm. consists of fine-grained terrigenous sediments, containing graptolites such as *Climacograptus latus*, *Cl. cf. scolaris*, *Dictyonema* sp., *Diplograptus* sp., *Ptilograptus* sp., *Glyptograptus* sp. and trilobites such as *Agnostus perrugatus*, *Remopleurides salteri* of Late Ordovician-Wenlock age. In the Quang Ninh province, the Tan Mai and Co To Fms. (Figures. 2&3) consist of turbiditic tuffaceous gritstone, siltstone, and sandstone (Figure 6A-C) interbedded with black shale containing Early Silurian graptolite (*Spirograptus turriculatus*, *Campograptus communis*, *Monograptus priodon*, *Demirastrites triangularis*) (Tran and Vu, 2011, pp. 60–62). On the Co To island, excellent outcrops of Late Ordovician-Early Silurian rocks with a youngest peak detrital zircon U-Pb of 440 Ma (Rizzi et al., 2020) show slope to deep-water turbiditic facies (Figure 6A-C; Bui H. H. et al., 2018).

Late Silurian deposits in North East Vietnam are only found south of Hai Phong City (Figure 1) and are attributed to the Kien An Fm. (Figure 3). It consists of blue-gray marl, mudstone, sandstone and limestone lenses containing brachiopods (*Retziella webery*, *Eospirifer tingi*) and corals (*Favosites mamillatus*, *Nipponophyllum nikolaevae*), signifying a

shallowing upward trend from the deep-water Early Silurian deposits (Tong and Vu, 2011, pp. 91–92).

North West Vietnam

In North West Vietnam, Late Ordovician-Early Silurian deposits lie unconformably on older rocks and are attributed to the Sinh Vinh Fm. to the NE and the Ket Hay Fm. to the SW (Figure 3). The Sinh Vinh Fm. consists of basal conglomerate and coarse-grained arkosic sandstone grading upward into light gray, thickly bedded dolomitic limestone, sandy limestone and marl containing abundant corals (*Plasmoporella kiaeri*, *Favosites* aff. *Forsberi*, *Favositella alveolatus*, *Parastriatopora* sp.) and crinoids (Tran and Vu, 2011, p. 62). This indicates a shallow marine environment, similar to that over the Yangtze Block and in sharp contrast to the coeval deep-water environment in North East Vietnam. Grading upward, the Bo Hieng Fm. (Figures. 2&3) consists of marly shale and limestone with corals, brachiopods and bivalves similar to those found in South China and Eastern Australia (Tong and Vu, 2011).

To the north of the Song Ma suture, the Ket Hay Fm. dominantly consists of deep-water shale and cherty shale containing Late Ordovician graptolites such as *Rastrites* sp., and further up section *Demirastrites triangulatus*, *Hedrograptus* cf. *rectangularis*, *Diplograptus* cf. *modestus* of Llandovery age (Tong et al., 2013; Tran and Vu, 2011, pp. 62–63). The lithological and fossil assemblages of the Ket Hay Fm. are similar to the Song Ca Fm. in the Viet-Lao terrane.

3.3.2. Indochina composite terrane

During the Early-Middle Ordovician, arc-affinity volcanism was distributed from western Kon Tum to northern Laos in a NW-SE trend. In Donken, SE Laos (Figure 1), calc-alkaline and tholeiitic magmatism with volcanic arc affinity crops out west of the Po Ko suture. Diorite and rhyolitic tuff yields zircon U-Pb ages of 470 ± 2 Ma and 476 ± 1.5 Ma, respectively

(Gardner et al., 2017). West of Quang Binh province near the Vietnam-Laos boundary, arc-affinity calc-alkaline granodiorite and granite of the Vit Thu Lu complex with zircon U-Pb age of 475 ± 5 Ma intruded into the Long Dai Fm. (Figures. 2&3; Bui, 2010, p. 58; Le D.B. and Bui M.T., 2008). Within the Kon Tum terrane, I-type granodiorite of the Dien Binh complex displays zircon U-Pb isotopic ages of 470-468 Ma in the Po Y area (Nguyen et al., 2018), 445 Ma in the Tra Bong area (Nguyen et al., 2015), and 444 ± 17 Ma and 451 ± 3 Ma in the Dien Binh area (Carter et al., 2001; Nagy et al., 2001). S-type granitic intrusions of the Chu Lai Complex yield zircon U-Pb LA-ICP-MS ages of 444-426 Ma (Dinh, 2017), and the Dai Loc Complex yield ages from 427 to 406 Ma (Carter et al., 2001; Pham et al., 2016). The Huoi Tong massifs in west Dien Bien (Figure 1) are dated as 446-415 Ma (Nguyen V. N. et al., 2005).

Deposits of the Middle Ordovician to Silurian mega-episode are found both in the Viet-Lao and Viet-Cambodia terrane, characterized by two distinct successions: the Middle Ordovician-Early Silurian is dominated by deep-marine fine-grained sediments while the Late Silurian is characterized by a depositional environment changing from shallow to deep-water. During the Middle Ordovician-Early Silurian, deep-water environment is recorded by the Song Ca Fm. and Long Dai Fm. in the north and south, respectively. The Song Ca Fm. is about 2000 m thick and is distributed north of the Song Ca Fault. It consists of Early Silurian graptolite-bearing shale, fine-grained sandstone and some bedded limestone interbedded with 440 Ma rhyolite (Tran Trong Hoa and T. Usuki, personal communication). The Long Dai Fm. is about 2000-2500 m thick and extends from north and west of the Kon Tum terrane to northern Central Vietnam and northeast Laos (Nguyen, 1997; Phan et al., 2009). Resting unconformably on the A Vuong Fm., it consists of a basal conglomeratic unit (70 - 90 m thick) and coarse-grained graywacke sandstone in the lower part (Figure 6D-F), and pass upward into Late Ordovician trilobite-bearing siltstone, sandstone, striped cherty shale, and Llandovery-Wenlock radiolarian and graptolite-bearing black shale (Dovjikov, 1965, pp. 210–212; Nguyen V. P., 2000; Tran

and Vu, 2011, p. 64). Interbeds of intermediate to felsic volcano-clastic rocks are also recognized. The sandstone contains fragments of felsic and mafic effusives, crystalline schist and granite, and its composition indicate a volcanic arc origin (Yoshida et al., 2002). The volcanic beds can also be correlated to similar deposits in Laos (Thassanapak et al., 2017).

During the Late Silurian, the deep-water depositional environment of the Song Ca Fm. and lower Tay Trang Fm. persisted in the northwest, while to the south the shallow marine siliciclastics of the Dai Giang Fm. (Figures. 2&3) dominated, containing a rich benthic fauna such as trilobites, corals, bivalves, and fishes (Tong et al., 2013). However, in the Sepon mine, Laos (Figure 1), Ludlow-Pridoli radiolarian cherts indicate basin deepening toward the southwestern margin of the Viet-Lao terrane (Thassanapak et al., 2017).

3.4. Devonian-Early Carboniferous (Tournaisian) mega-episode

In the Late Silurian- Early Devonian, orogenic-type batholithic intrusions formed in both the Indochina and Sino-Vietnam composite terranes outlined by the Dai Loc complex in Viet-Lao terrane and 428-415 Ma Song Chay complex in North East Vietnam (Roger et al., 2000; Yan et al., 2006). Devonian-Early Carboniferous sedimentary deposits in the Sino-Vietnam composite terrane and north Central Vietnam are characterized by shallow marine facies containing a rich benthic fauna (Duong, 1980; Tong et al., 2013). Along the western margin of Indochina, volcanic rocks in the Loei-Phetchabun terrane were dated as 349-304 Ma (Qian et al., 2016), while in the Kon Tum terrane a thermo-tectonic event was recorded at 360-340 Ma (Nagy et al 2001) and 366 Ma (M. Faure and Nguyen V.V., unpublished data). Fyhn et al. (2019) illustrated a 340 Ma peak in detrital zircon age spectrum in modern rivers draining the northern Kon Tum terrane and interpreted the zircons to imply the existence of unmapped Late Devonian-Early Carboniferous intrusions in this region similar to farther west.

The lowermost Devonian, consisting of nearshore gritstone and sandstone, rests unconformably on older rocks in the Sino-Vietnam composite terrane (Tran and Vu, 2011, p. 70; Xu et al., 2016), on Silurian rocks in Viet-Lao terrane, and even on granite in the western margin of the Kon Turn massif (Tong et al., 2013). In the North East Vietnam domain, the lower part of the Song Cau Group (Figure 3) contains fossil flora of *Taenioocrada* (?) sp., *Eospecia graciosa*, *Buthotrephis antiquata* and vertebrate remains of *Yunnanolepis* sp. (Tran et al., 1977, p. 73) while in the North West Vietnam domain, the Bo Hieng Fm. (Figure 3) contains *Taenioocrada* sp. (Ta and Le, 1996). Plant fragments as well as arthropod and fish remains are also found in the Do Son Group in the Hai Phong area (Figure 7A; Janvier et al., 2003; Long et al., 1990) and on the Ngoc Vung island, ESE of Ha Long Bay (Figure 1). Some authors argue that the Do Son Group may include the upper most part of the Silurian (Gonez et al., 2012; Janvier et al., 2003), and the plant fragments found on the Ngoc Vung island (Figure 1) represents the earliest known flora of the Sino-Vietnam composite terrane (Gonez et al., 2012).

Lower Devonian deep-water deposits belonging to the Song Mua Fm. and part of the Tay Trang Fm are limited to a few areas. The Song Mua Fm. is distributed along the Da River basin in North West Vietnam, consisting of predominantly black argillaceous shale up to 2300 m thick (Dovjikov, 1965). The Tay Trang Fm. is distributed along the Ca River basin in north Central Vietnam (Figure 1) and contains both deep and shallow water deposits juxtaposed laterally. The formation's deep-water facies consists of shale and siltstone bearing graptolite (*Monograptus zoniformis*, *M. praehercynicus*, *M. cf. aequabilis notoequabilis*, *M. thomasi*) and coniconchs (*Nowakia acuaria*, *N. elegans*, *Styliolina intermedia*, etc.) while shallow water facies contains crinoids (*Schyschcatocrinus* sp., *Cyclocyclicus* sp., *Anthinocrinus floreblus*, etc.) as well as fossil flora in NW Ha Tinh near the Viet-Lao border (*Zosterophyllum* sp., *Hostimella* sp., *Protoleiosphaeridium angulatum*) (Dovjikov, 1965, p. 191; Tran et al., 1977).

The Tay Trang Fm. may include some of the latest Silurian at its base (Tong and Vu, 2011; Tran and Vu, 2011).

The Middle and Upper Devonian consist of interbedded siliciclastics, carbonates and chert. The maximum Devonian transgression took place in the Givetian as shown by a large distribution of shallow water carbonate containing abundant bioherms and reef corals as well as conodont-bearing cherty deepwater facies (Figure 7B; Tong et al., 2013). In addition, in some places there are coal-bearing successions reflecting a transitional depositional environment ranging between marine influenced continental and shallow marine, such as the Middle Devonian Dong Tho Fm. distributed over a small part of northern Central Vietnam. This formation has a thickness of 1050 m, and consists mainly of sandstone, anthracite and coaly shale containing fossil flora such as *Protopteridium* sp., *Lepidodendropsis* sp. and brachiopods such as *Emanuella tumida*, *Chonetes* sp., *Undispirifer rudiferus* (Dovjikov, 1965, p. 227; Tong and Vu, 2011, pp. 196–198; Tran et al., 2016).

Along the southwest Vietnam and Cambodian margin towards the Gulf of Thailand, Devonian deposits of the Hon Heo Fm. consist of sandstone and siltstone interbedded with argillaceous shale containing flora remains (*Taeniocrada* (?) sp. and *Psilophyton* sp.) (Figure 3; Nguyen N.H., 1996).

Upper Devonian deep-water deposits are attributed to the Ngoc Lam Fm. in NW Quang Binh province (Ta, 1998) and Thien Nhan Fm. in Ha Tinh province. They contain rich pelagic faunas including tentaculitoids such as *Striatostyliolina striata* and *Styliolina* sp., and radiolarians such as *Entactinia cometes*, *Belowea variabilis*, and *Archocyrtium* (Nguyen et al., 2016). They grade upward into Tournaisian sediments containing the conodonts *Polygnathus fornicates* and *Gnathodus semiglaber* (Nguyen B. M. et al., 2013). In addition, deep marine deposits are also found in North West Vietnam (Toc Tat and Da Nieng Fms. (Doan and Ta, 2003)) and North East Vietnam (Lung Nam and Pho Han Fms.; Figure 7B), which contain

forams such as *Uralinella bicamerata*, *Eoendothyra communis*, *Quasiendothyra konensis* and is rich in conodonts such as *Palmatolepis gracilis*, *P. sigmoidalis*, *Spathognathodus disparilis* (Tran and Vu, 2011). Similar radiolarian-bearing cherty deposits occur in central Laos and the Loei region of NW Laos (Udchachon et al., 2015, 2017).

3.5. Carboniferous (Visean)-Middle Permian mega-episode

Over the interior of Indochina as well as within the Sino-Vietnam composite terranes, carbonate platform developed widely resulting in deposition of thick and homogeneous carbonate successions that rest unconformably on Devonian-Tournaisian formations (Tong and Vu, 2011, p. 230; Tran and Vu, 2011, pp. 99–102). In addition, Serpukhovian coal-bearing sediments in Central Vietnam, southern Laos, NE Thailand and Cambodia are also found resting unconformably on Devonian and Tournaisian-Early Visean strata (Ha et al., 2009; Hoffet, 1933). These sediments were deposited in terrestrial swamps and paralic environment (Tran et al., 2016; Ueno and Charoentitirat, 2011). Meanwhile, volcanic series roughly of the same age were widespread in the western margin (Sukhothai arc, Loei-Phetchabun belt, northern Cambodia, central and southwest Vietnam).

3.5.1. Indochina composite terrane interior (NE Vietnam-N Laos-NE Thailand)

The Carboniferous-Middle Permian deposits in this area (Figure 8) are dominated by continental shelf carbonates. The Bac Son Fm. consists largely of about 800-1000 m thick of limestone and dolomite with chert interbeds and lenses, bearing Early Carboniferous-early Late Permian brachiopods, corals and foraminifera (Nguyen, 1985). In NW Laos, along the Nam Ou, Nam Tha River as well as in Luang Prabang, west Vientiane and in northern part of northeast Thailand, the Late Carboniferous-Permian consists of thinly bedded shale and limestone bearing fossils such as *Schwagerina princeps*; *Pseudofusulina gigantea*, *P. jappnica*, coaly-shale bearing Cathaysian-affinity plant fossils such as *Carbonicola*, *Gigantopteris*

nicotinae foliae, *Pecopteris arcuata*, as well as andesite tuffs and siltstone (Saurin, 1956). In SW Vietnam and southern Cambodia, the Early-Middle Permian Ha Tien Fm. consists mainly of limestones containing abundant *Parafusulina loeyensis* and *Codonofusiella* sp. (Figure 9).

Early Carboniferous coal-bearing swamp sediments occurred in Salavan, Attapeu and NW of Vientiane in Laos (United Nations, 1990); and in Sisophon, Kratie, Peam Pros, Bos Dambang, and Kampot in Cambodia (Fontaine and Workman, 1978; United Nations, 1993); as well as in La Khe in north Central Vietnam, and in the northern part of northeast Thailand (Rattanasathien, 2011). In Salavan, SE Laos, resting unconformably on Early Famennian limestone, the sediments have a thickness of 300-400 m and consist of a thick basal conglomerate, grading upward into sandstone, black-grey calcareous siltstone, and anthracite seams (Ha et al., 2009; Tran, 2000). They yield abundant Late Visean-Early Serpukhovian plant fossils such as *Stigmaria rugulosa*, *Pecopteris aspera*, *Calamites* cf. *sukowi*, *Lepidophyllum trigeminum* of Cathaysian affinity and bivalves such as *Aviculopecten* cf. *dupontesi*, *Astartella lutungini* (Ha et al., 2009; Hoffet, 1933; Saurin, 1956). In the Na Duang coal mine in Loei province in NE Thailand, conglomerates, tuffaceous sandstone and coaly shale contain abundant basal Bashkirian terrestrial plant remains such as *Stigmaria ficoides*, *Lepidodendron timsuwanii*, *Eusphenopteris* sp., *Adiantites* sp. These plant fossils have similarities to the South China floras (Laveine et al., 2009, Rattanasathien, 2011).

3.5.2. Western Indochina margin (NE Thailand, NW Vietnam-Laos–Cambodia-SW Vietnam)

The Latest Carboniferous-Early Permian intermediate volcanic series and I-type granitoids are distributed around the western periphery of the Indochina composite terrane (Figure 8). They are found along the Vietnam-Laos border (Bui, 2010), in the Siem Riep-Stung Treng region in Cambodia, in the Loei-Phetchabun, Lampang, Chanthaburi and Sra Kaeo volcanic belts in Thailand (Barr and Charusiri, 2011; Charusiri et al., 2002; Salam et al., 2014;

Sone et al., 2012) and in the Kuantan-Sungei Lembing region in eastern Malaysia (Burrett et al., 2014; Hutchison, 2007; Metcalfe, 2013).

In western Indochina and SW China, the Carboniferous-Early Permian volcanic rocks consist of various compositions of andesites, dacites and basalts. The basaltic rocks in the central Loei area were linked to ocean-floor and ocean-island, while calc-alkaline porphyritic andesite and associated plutonic rocks in Wang Pong area formed above an east-dipping subduction zone underneath Indochina (Barr and Charusiri, 2011; Charusiri et al., 2002; Pham and Ta, 2003). The continuation of the Loei belt in NW Laos contains 349-330 Ma andesitic, rhyolitic and tuffaceous deposits, as well as ~315 Ma basalts and andesites of continental arc affinity (Qian et al., 2015). In the Sukhothai arc, Late Carboniferous-Permian volcano-sedimentary successions of limestones, sandstones, shales and chert are interbedded with felsic to intermediate volcanic rocks. An Early Permian age is indicated by the presence of fusulinids (*Pseudoschwagerina* sp.), and radiolaria (*Pseudoalbaillella simplex*, *P. lomentaria*, *P. scalprata*) as well as stratigraphic relationship with over- and underlying rocks (Ueno and Charoentitirat, 2011).

In North West Vietnam, the Early Permian volcano-sedimentary Song Da Fm. is distributed mainly along the right side of the Da River (Lai Chau and Dien Bien provinces) (Figures. 8&9; Dovjikov, 1965, pp. 198–200). It is composed of 280 m thick of conglomerate, gritstone, and sandstone interbedded with siltstone and shale. Upward, it grades into 350 m thick of andesitic basalt, felsitic dacite, thin-bedded cherty shale, and limestone. The upper part is composed mainly of 700 m thick of bedded limestone containing *Pseudofusulina* sp. *Misellina ovalis* of Early Permian age interbedded with tuffaceous shale and marly shale (Tran and Vu, 2011, pp. 245–247). In the SE, the I-type gabbrodiorite, granodiorite, and granite of the Dien Bien Phu Complex intrude the volcano-sedimentary beds of the Song Da Fm. The

granitoids yield zircon U-Pb LA-ICP-MS ages ranging from 281 to 272 Ma (Liu et al., 2012; Tran and Nguyen, 2006).

In NW Laos, the Early Permian Houayxay Fm. consists of dacite, rhyolite, and tuff conglomerate containing brachiopod (Strophomera indet., *Lingula* sp., Schuchertellidae gen. indet., Productida fam. gen. indet.). The volcanic rocks have similar lithological and geochemical characteristics to that in the Houayxay gold mine, yielding a zircon U-Pb LA-ICP-MS date of 286 ± 4 Ma (Early Permian) (Manaka et al., 2014). In southern Laos, continental arc magmatism during the Early Permian is documented at the Sepon gold mine, characterized by ca. 295–288 Ma U-Pb LA-ICP-MS ages (Khin Zaw et al., 2014).

Along the Vietnam-Laos border (Vit Thu Lu, Quang Binh province), the Dong Toan Fm. consists of tuff-andesite, andesitic basalt, and andesite interbedded with clastic sediments. Its age is based on the occurrence of Carboniferous-Permian corals and crinoids and Late Permian brachiopod as well as the stratigraphic relation to underlying Middle Permian carbonates. Their geochemical characteristics are compatible with subduction-related island arc magmatism or an active continental margin setting (Bui, 2010, p. 70).

In the Srepok River Basin near the Vietnam and Cambodia border, the Dak Lin Fm. is composed of intercalating thin bedded cherty shale, porphyritic andesite, andesitic basalt, rhyodacite, tuffs, and limestone that contain *Schwagerina* sp., *Pseudofusulina* sp., *Verbeekina* sp. of latest Carboniferous-Early Permian age (Tran, 1996). These volcano-sedimentary sequences extend into NE Cambodia. Volcano-sedimentary sequences of Late Carboniferous-Permian age are also indicated in the Siem Riep-Stung Treng region of Cambodia (United Nations, 1993). In addition, diorites, granodiorites, and granites of the Ben Giang-Que Son complex exposed in the Kon Tum metamorphic terrane yield zircon U-Pb ages around 303-295 and 261 Ma (Nguyen and Tran, 2016). These igneous rocks show high LILE enrichment relative to HFSE,

high LREE and low HREE (Figure 10), which are typical of island arc and active continental margin (Bui M.T., 2010; Tran et al., 2005).

Offshore Cambodia and SW Vietnam, on the Hon Mau, Hon Chuoi, Hon Buong and Nam Du islands (Figures. 8&9), thinly bedded andesitic and rhyodacite tuffs of the Nam Du Fm. are dated by zircon U-Pb LA-ICP-MS at around 279 Ma (Early Permian) (Fyhn et al., 2016). The formation also contains turbidite and cherts bearing Late Carboniferous radiolaria. These grade laterally into Early-Middle Permian siliciclastics and limestones of the Ha Tien Fm. dated by brachiopods and foraminifera assemblages. The age of the Nam Du Fm. is further constrained by the overlying Middle-Late Permian Dat Do Fm. containing *Beecheria* sp. and *Neospirifer* sp. (Tran and Vu, 2011).

3.6. Late Permian-Early Triassic mega-episode

Late Permian volcano-sedimentary rocks are exposed widely in north Vietnam and south China but more scattered in other areas of the Indochina peninsular. They rest unconformably upon older rocks. A number of volcanic rift systems developed in north Vietnam, including the Song Da, Tu Le, Song Hien, and the An Chau rift systems (Figure 8). The volcanic deposits of the Song Da-Tu Le rift systems are assigned to the Cam Thuy Fm., which consists of porphyritic high titanium basalt, ferrous allite, and tuffaceous siltstones (Figure 9), dated as 255 Ma (Tran et al 2016). Meanwhile, igneous rocks in the Song Hien rift ranges in composition from ultramafic-mafic to felsic, dated as 266-260 Ma (Izokh et al., 2005; Tran et al., 2008). In addition, widespread 260-248 Ma anatectic S-type granites occurs in the Viet-Lao terrane (Figure 8; Shi et al., 2015; Tran and Vu, 2011).

In NE Vietnam and Battambang-Sisophon (Cambodia), a regional uplift triggered the karstification of the Carboniferous-Permian limestone and led to coal and bauxite deposition

(Tran and Vu, 2011; United Nations, 1993). In NE Vietnam, bauxites are found at the base of the Dong Dang Fm., which consists mainly of thinly bedded limestone, shale, and cherty limestone containing Changhsingian fusulinids (*Palaeofusulina prisca*, *Colaniella parva*, *Reichelina pulchra*) as well as brachiopods and calcareous algae (Nguyen, 1985; Tran and Vu, 2011, pp. 107–108).

Late Permian coal-bearing deposits are scattered throughout north Vietnam, NW Lao and SW Cambodia. In the Song Da rift, the Yen Duyet Fm. (Figure 9) overlies volcano-sedimentary beds and consists of carbonaceous shales, coal seams, and limestones. It contains leaf imprints such as *Gigantopteris nicotianaefolia*, *Lobatannularia multifolia*, *Pecopteris anderssonii*, *Taeniopteris multinervis* (Nghiem, 2018; Nguyen, 1984) and Late Permian brachiopods such as *Leptodus* sp., *Oldhamina* cf. *decipiens*, *Neophricodothyris* cf. *asiatica*. Further to the southwest in NW Lao (Nam Ou) and NE Cambodia, Late Permian coal occurs in the form of thin lenses (Fontaine and Workman, 1978; United Nations, 1990, 1993). In addition, in Luang Prabang, NW Laos, Cathaysia-affinity *Dicynodon* cranial and postcranial elements are found in the Purple Claystone Fm. (Luang Prabang Fm.), indicating a land connection between the Indochina and Sino-Vietnam composite terranes (Bercovici et al., 2012). Middle to Late Permian Cathaysian affinity flora are also found in this area, such as *Sphenopteris taiyuanensis*, *Lobatannularia ensifolia*, *Gigantonoclea* sp., *Rajaia guizhouensis* (Bercovici et al., 2012).

4. New zircon U-Pb data

In addition to the review of published literature, we have carried out field surveys to refine geological boundaries, as well as taken samples in various terranes in Indochina and the surrounding areas.

4.1. Sampling and analytical methods

In this section, we describe briefly the locations, zircon features from cathodoluminescent images and the results of U-Pb dating by LA-ICP-MS method for 16 samples (Table 1 and Appendix 1). The analyzed samples are from unmetamorphosed, mostly felsic to sub-alkaline volcanic and plutonic rocks, except for sample OG9 collected from a gabbro. Zircon U-Pb geochronology was carried out on mineral separates embedded in epoxy mounts by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) following the standard procedures at the Geological Survey of Denmark and Greenland (GEUS), Kyushu University, Japan, the Geological Survey of Japan (AIST) and Institute of Earth Sciences, Academia Sinica, Taiwan (IESAS). The cathodoluminescent images of analyzed zircon minerals show euhedral shape (Figure 11).

4.2. Zircon geochronological results

Calculation of errors and correlation of the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios follow the procedure of Ludwig (2008) using the program ISOPLOT 4.15. The concordia diagrams for the analyzed samples are shown on Figure 11. The detailed analysis data table is included in Appendix 1. The dating results show three age groups: 444-443 Ma (Early Silurian), 301-278 Ma (Late Carboniferous-late Early Permian), and 258-250 Ma (latest Late Permian). The significance of these results will be discussed in the corresponding mega-episodes in the following section.

5. Discussion of a possible geodynamic evolution

Based on regional unconformities of Early Ediacaran, early Middle Cambrian, Dapingian, Late Pridoli, Early Visean, Late Wuchiapingian and Late Olenekian ages (Figures. 2&3), litho-biostratigraphy, peak metamorphic ages, peak magmatic ages, and geological relationships, we recognized six Neoproterozoic to Early Triassic tectono-stratigraphic mega-episodes in Indochina and adjacent areas (Figure 12; Tran et al., 2018).

5.1. Neoproterozoic-Early Cambrian evolution

During the Neoproterozoic-Early Cambrian mega-episode, branches of the Proto-Tethys, including the Proto-Song Ma Ocean and the Tam Ky-Phuoc Son Ocean, separated the Sino-Vietnam (South China) terrane from the Indochina terranes (Figure 12A). Popular views of the Song Ma oceanic crust suggested a Devonian-Carboniferous age based on ophiolite dating along the Song Ma suture (Nguyen V.V. et al., 2013; Zhang et al., 2014). However, recent evidence suggests that an older Proto-Song Ma Ocean existed during the Neoproterozoic-Early Cambrian, which closed before the Middle Cambrian.

First, the 470 Ma gabbroic intrusion into the chromite-bearing Nui Nua serpentized complex (Figure 1; Pham et al., 2014) indicates the presence of an oceanic crust older than that documented by Nguyen V.V. et al. (2013).

Second, the Nam Co subduction accretionary complex and the Posen I-type granite (760-750 Ma) is interpreted to record Neoproterozoic northward subduction of a Proto-Tethys branch under the southwestern Sino-Vietnam composite terrane. Detrital zircon U-Pb ages from meta-sandstones are unimodal and yield a major peak centered around ~850 Ma, characteristics of a magmatic arc setting (Bui V. H. et al., 2018). The detrital zircon U-Pb age distribution is comparable to that of the southern Yangtze Block, but differs from Indochina or Cathaysia, indicating a primary detrital input derived from the southern Yangtze Block (Bui V. H. et al., 2018).

Third, subduction-related magmatism is also well documented along the SW margin of the Ailaoshan suture zone (Cai et al., 2014) as well as along the northwest margin of the Yangtze Block (Dong et al., 2012).

Fourth and finally, the similar lithology and benthic fauna of Middle Cambrian-Early Ordovician deposits on both side of the Proto-Song Ma suture (see section 5.2) suggest that the

suturing of the Sino-Vietnam and Viet-Lao terranes occurred in the Early Cambrian or Late Neoproterozoic (Figure 12B). This is coeval with the Pan-African orogenesis, in which many Proterozoic continents amalgamated to form the Gondwana supercontinent (Torsvik and Cocks, 2017).

Since the Early Cambrian, a shallow marine shelf setting existed over the Hoang Lien Son-Ailaoshan terrane and southern Yangtze block resulting in carbonate and phosphate deposition. This setting was located far north of the Proto-Song Ma suture and extends to over the southern Yangtze block. Meanwhile, similar settings also developed in Australia, India, Korea, NW China and Mongolia; and this time period is recognized as one of the greatest phosphogenic episodes in geological history (Cook and Shergold, 2005).

During the same period, north of the Kon Tum terrane, the Tam Ky-Phuoc Son ocean, as documented by 518 Ma and 502 Ma trondhjemite-tonalite suite (Nguyen et al., 2019) extracted from the Kham Duc complex, still separated the Kon Tum terrane from other terranes of Indochina (Figure 12B).

5.2. Middle Cambrian-Early Ordovician evolution

During this time, in the Sino-Vietnam composite terrane, shallow shelf carbonate deposition dominated to the NW and a rich benthic trilobite and brachiopod fauna thrived (Chang Pung and Lutxia Fms.) (Figures. 2&3), similar to the sedimentary cover of the Yangtze Block. Meanwhile, deep-water sediments containing agnostidae cold-water trilobites and graptolite (Than Sa Fm.) formed in the SE along the Jiangnan zone. In addition, the lithological and paleontological characteristics of the North West Vietnam domain are very similar to the North East Vietnam domain and Yunnan (China) (Pham, 2008). The trilobites in the Late Cambrian-Early Ordovician Chang Pung and Ham Rong Fms. in northern Vietnam are also similar to those in the Tarutao Group in south Thailand (Pham, 2008, p. 158; Shergold, 1995;

Wongwanich and Burrett, 1983). These lines of evidence suggest that in Early Paleozoic times, the Sino-Vietnam composite terrane, Viet-Lao terrane and Viet-Cambodia terrane formed part of a single continent, or were situated closely to each other (Figure 12B; Burrett et al., 2014; Tran and Vu, 2011, pp. 116–118).

To the north and west of the Kon Tum terrane, volcano-terrigenous sediments of the deep-water A Vuong Fm. formed in an island arc setting associated with the northward subduction of the Proto-Tethys under the Viet-Lao/Phu Hoat terrane (Tran, 1979, pp. 56–57., Tran et al 2018), which by then was already amalgamated to the Sino-Vietnam composite terrane (Faure et al., 2018). The subduction might also have been directed southward, as suggested by the Nui Vu and Phong Hanh volcano-plutonic arc complex (Figures. 2, 3 & 12B) (Gardner et al., 2017; Tran et al., 2014., Tran, 1998; Tran and Vu, 2011, pp. 59–60).

During this time, Indochina and South China were adjacent to Gondwana, sharing the same sediment source (Burrett et al., 1990, 2014; Usuki et al., 2013). North China, South China and the Lhasa block were all in a largely similar faunal province, suggesting their close geographical location in the Middle Cambrian (Torsvik and Cocks, 2017).

5.3. Middle Ordovician-Silurian evolution

Tectonically, this mega-episode is characterized by the Early Paleozoic orogeny. In the Sino-Vietnam (South China) composite terrane, the orogeny was an intra-continental one (e.g. Charvet et al., 2010; Faure et al., 2009), which in North East Vietnam resulted in slope to deep-water flysch sedimentation of conglomerate and sandstone interbedded with graptolitic shale. The orogeny initiated along the north and NW margins of the former Cathaysia Block, causing a shallowing upward depositional trend and NW-ward migration of shallow water conditions, while a stable carbonate-dominated shelf still continued to exist over most of the Yangtze Block (Charvet, 2013; Shu et al., 2015; Xu et al., 2016). A similar situation exists in North East

Vietnam. Meanwhile, in North West Vietnam, shallow marine shelf existed throughout the Late Ordovician-Silurian, which is consistent with this domain being on the southwest margin of the Yangtze Block during the Early Paleozoic, before being laterally displaced by Cenozoic escape tectonics (Faure et al., 2018; Leloup et al., 2001; Tapponnier et al., 1990; Tran and Vu, 2011, pp. 519–523).

In the Indochina composite terrane, possible bivergent subduction of the Tam Ky-Phuoc Son ocean underneath the Kon Tum terrane, Viet-Lao terrane, and Viet-Cambodia terrane (470–450 Ma) has been suggested (Gardner et al., 2017). This was followed by an Ordovician continental collision (450–425 Ma) that caused high-grade metamorphism and widespread migmatization in the Kon Tum massif. The northward subduction under the Viet-Lao terrane and Viet-Cambodia terrane (Faure et al., 2018) is indicated by: 1) the Late Ordovician-Early Silurian Long Dai volcano-plutonic arc which includes the Dai Loc S-type granites and felsic volcanic series in Donken, Laos (Gardner et al., 2017; Thassanapak et al., 2018); 2) the volcano-sedimentary Long Dai Fm. (Figures 2&3) and its equivalence in Laos as well as the Song Ca deep-water sediments, which probably formed in a back-arc basin (Figure 12C). The southward subduction is indicated by the 476–450 Ma I-type calc-alkaline diorite-granite Dien Binh complex (Figure 12C). The relicts of the consumed ocean are preserved as dismembered ophiolites along sutures flanking the Kon Tum terrane such as the Tam Ky-Phuoc Son suture (northern margin), Po Ko suture (western margin), and possibly also the Chu Sinh suture (southern margin). Faure et al. (2018) considered the Kon Tum terrane to be the exposed lower crust of the Viet-Cambodia terrane. However, the presence of the Chu Sinh suture, if recognized, would suggest that the Kon Tum massif might have been a separate terrane.

The metamorphism of the Kham Duc and Nui Vu complexes at 450 Ma (Usuki et al., 2009) as well as U-Pb dates at 468.6 ± 1.5 Ma of granulite in the Song Bien area (Roger et al., 2007) signify the complete closure of the Vietnam part of the Tam Ky-Phuoc Son ocean as

early as the Middle Ordovician. This is accompanied by 444-443 Ma S-type migmatitic granites of the Chu Lai complex in the Kon Tum terrane (sample OG08) and granites from the Viet-Lao terrane (sample DH13) (Figure 11). The closure timing is compatible with the basal conglomerate of the Late Ordovician-Early Silurian Long Dai Fm. Subsequent uplifts are indicated by a number of younger unconformities overlain by conglomerate beds such as the Late Silurian unconformity separating the Long Dai and Dai Giang Fm., the end-Silurian unconformity separating the Dai Giang Fm. and the Tan Lam Fm. in Viet-Lao terrane (Figures 2&3), as well as the significant Early Carboniferous unconformity in both Vietnam and Laos (Figure 9). This suggests that the collision between the Kon Tum and Viet-Cambodia terranes with the Viet-Lao terrane might have been diachronous, starting in north Kon Tum and younging northwestward to north Laos and northeast Thailand. The similar timing between these two Early Paleozoic orogenies, being intracontinental in Sino-Vietnam, and collisional in Indochina, led Faure et al. (2018) to argue for the suturing along the Tam Ky-Phuoc Son zone as the driving force for the intra-continental orogeny in South China, instead of a collision between South China and Australia as earlier proposed (Xu et al., 2016).

Following this event, the Indochina and Sino-Vietnam composite terranes might have formed a single landmass since at least the Late Silurian and Devonian. This is supported by the similarity in lithofacies as well as marine shelly fauna and flora fossils (Janvier et al., 1997; Tong et al., 1996). The depositional environment changed from deep-water into shallow marine in NE Vietnam (Kien An Fm.) and in the southern Viet-Lao terrane (Dai Giang Fm.). Meanwhile, a deep marine environment persisted throughout the Late Silurian within northern Viet-Lao terrane (Song Ca Fm. and lower Tay Trang Fm.) (Figures 2&3), and at the southwestern margin of Viet-Lao terrane (Thassanapak et al., 2018). Recently, Loydell et al. (2019) interpreted the Early Silurian graptolites found in the Viet-Lao terrane to reflect mid to high latitude, closer to peri-Gondwana Europe and Arabia than South China, which laid in a

low latitude position. This conclusion was based on the identification of stenothermic species of graptolite, the distribution of which were dominantly controlled by sea surface temperature, which in turn was used to infer their paleolatitude. However, as also noted by Loydell et al. (2019), the disposition of continents could have deflected warm current polewards and cold water equatorwards, thereby increase the latitudinal range of these species. Therefore, the paleolatitude difference between the Sino-Vietnam and Indochina composite terranes might not have been so large.

In addition, Late Ordovician-Early Silurian shelly faunas of South China (Sino-Vietnam) are closely related to coeval faunas on the Sibumasu composite terranes (Metcalf, 2013). The Sino-Vietnam-Indochina superterrane may have separated from Gondwana before the Devonian, probably in the Middle-Late Silurian (Burrett et al., 1990; Torsvik and Cocks, 2017; Young and Janvier, 1999).

5.4. Devonian-Early Carboniferous (Tournaisian) evolution

During this mega-episode, the tectonic regime was mostly stable. A passive continental shelf developed and marine transgression occurred over most of the study area (Figure 12E), while the western Indochina margin was in an active setting (Qian et al., 2016). The Devonian-earliest Carboniferous sequence is floored by a coarse-grained siliciclastic unit deposited unconformably on older rocks. This unit transitions upward into shallow marine carbonates and manganese-bearing siliceous shales. Fauna and flora in the Sino-Vietnam and Indochina composite terranes do not show relationship to those in Gondwana since the Devonian-Early Carboniferous, indicating that these terranes had drifted away from peri-Gondwana by this time (Golonka, 2006; 2012; Metcalfe, 2013). Since the late Middle Devonian, the Song Ma ocean reopened as evidenced by the ultramafic rocks with a Sm-Nd age of 387 Ma (Nguyen V. V. et al., 2013), and zircon U-Pb SHRIMP ages from 340 to 330 Ma (Zhang et al., 2014). Meanwhile, some deep-water deposits are preserved in narrow continental troughs in north Central Vietnam,

southern Laos, NW Laos and NE Thailand. The Late Devonian chert deposits in Loei were interpreted to have formed in a back-arc basin developed on continental crust, based on the intercalation with mafic volcanic beds, and the presence of shallow marine sandstone and limestone underlying the chert (Udchachon et al., 2015, 2017).

5.5. Early Carboniferous (Visean)-Middle Permian evolution

The tectono-stratigraphic evolution of this mega-episode resulted in the establishment of stable carbonate platform in the Sino-Vietnam composite terrane and eastern Indochina, as well as coal bearing deposits in Laos and NE Thailand containing abundant *Cathaysia*-affinity plant fossils (Laveine et al., 2009; Ueno and Charoentitirat, 2011). During the Early Carboniferous, the Song Ma ocean was still present as a Paleo-Tethys branch that separated the Sino-Vietnam and Indochina composite terranes (Figure 12E&F), as discussed in the previous section. The Song Ma ocean might have extended into the Bangxi-Chengxing tectonic zone in the middle Hainan Island where oceanic basalt dated 330 Ma by zircon U-Pb exists (He et al., 2018). However, this was probably a narrow ocean (Faure et al., 2014; Metcalfe, 2013), due to similarities in the flora and fauna on both side of the Song Ma suture. Meanwhile, detrital zircon U-Pb analysis of Permian-Triassic marine sediments in NE Thailand indicates the beginning of arc activity in the Sukhothai Arc during the Late Carboniferous to Early Permian (Hara et al., 2015).

Some authors have suggested the existence of an oceanic crust between north Vietnam and South China, of which remnants are preserved along the so-called Dian Qiong suture. Along this zone, Early Carboniferous-Permian gabbro, pillow basalts, and mafic dykes have been found in in NE Vietnam, Yunnan, and Guangxi Provinces, and were interpreted as the “Babu ophiolites” (Cai and Zhang, 2009; Halpin et al., 2016; Liu et al., 2018; Tran et al., 2007). However, their geological setting, as intrusions within Carboniferous platform carbonates, and

geochemistry show that they are intraplate basalts corresponding to remote parts of the Emeishan Large Igneous Province (Faure et al., 2014, 2016; Izokh et al., 2005).

Widespread island arc and active margin volcano-plutonic assemblages (300-270 Ma) developed throughout NW Vietnam, Laos, NE Thailand, Cambodia, SW Vietnam, the Gulf of Thailand and East Malaysia, stretching for more than 2000 km from north to south (Figure 8; Tran et al., 2015, 2018). This is further supported by our new data from the Gulf of Thailand (samples 538333, 538329, 453011, 453014, and 453015) and Cambodia (sample 538736) (Figure 11). Different models have been proposed to explain the distribution of this volcanic belt. The western margin can be explained by eastward subduction of a branch of the Paleo-Tethys under the Indochina composite terrane (Morley, 2018) or associated back-arc basin development (Qian et al., 2016; Rossignol et al., 2016). In NW Laos, the magmatism was attributed to the subduction under the Viet-Lao terrane of oceanic crust attached to the Sino-Vietnam composite terrane (Kamvong et al., 2014), possibly referring to the Song Ma oceanic crust. However, we prefer eastward subduction of a branch of the Paleo-Tethys under Indochina as the main driver for the widespread magmatism (Figure 12F), since the Song Ma ocean, as argued above, was too narrow for its subduction to have significant influence.

After being separated from Gondwana since the Middle-Late Silurian, South China and Indochina drifted northward and were in a low latitude position by the Late Carboniferous (Li et al., 2004). Sibumasu was part of Gondwana's Himalaya–Australian margin until the Early Permian (Sakmarian). However, during the late Early Permian, Sibumasu drifted rapidly northward away from Gondwana and entered into warm-climate equatorial Cathaysian faunal province in the Late Permian (Metcalf, 2013, 2017).

5.6. Late Permian-Early Triassic evolution

This mega-episode was characterized by Late Permian-Early Triassic intra-continental rift systems possibly triggered by the 260-257 Ma Emeishan Large Igneous Province mantle plume event, and resuturing between Indochina and Sino-Vietnam composite terranes. These rift systems were filled by mafic to felsic volcanic complexes with both high-Ti and low-Ti compositions. The rifting reached its climax at 257 ± 3 Ma (Tran T.H. et al., 2016). Our ca. 258 Ma rhyolites from the Tu Le rift (samples TT01 and TT02) from the North West Vietnam domain, and 256-250 Ma granosyenite and granite (samples CH01, CH02, NS1 and NS2) from the North East Vietnam domain (Figure 11) are consistent with this tectonic setting in the Late Permian. In addition, the 250 Ma gabbro from the Kon Tum terrane (sample OG9, Figure 11) might be due to plume-related magmatism in the Late Permian (Nakano et al., 2013; Osanai et al., 2008; Owada et al., 2016). This mantle heat source may play a key role in the Late Permian-Early Triassic tectonic exhumation and metamorphic core complex formation over the Kon Tum terrane that overprinted the earlier Ordovician metamorphic event (Faure et al 2018).

The rewelding of Indochina and Sino-Vietnam along the Song Ma suture is evidenced by a large Indosinian orogenic belt consisting of widespread anatectic S-type granites (260-248 Ma) in the Viet-Lao terrane (Figures. 8 & 12G), and Late Permian-Early Triassic high to ultra-high pressure metamorphic rocks of LT eclogite and HP granulite along the Song Ma suture zone (Nakano et al., 2008; Zhang et al., 2014). This event created a single vast landmass as indicated by similar plant remains and faunas found in both the Sino-Vietnam and Indochina composite terranes (Bercovici et al., 2012). In particular, rich Cathaysian flora is found in coal-bearing deposits scattered throughout N. Vietnam, NW Laos, E. Thailand, SW Cambodia (see part 3.6 for more details). These deposits and their flora indicate a warm and wet climate, close to the equator. This is consistent with paleomagnetic studies of basalts in the Song Da rift,

which put NW Vietnam's paleolatitude at $\sim 5^{\circ}\text{N}$ or 5°S during the Late Permian (Geissman et al., 2018).

Meanwhile, the Gondwana genus *Glossopteris* are found in Phetchabun, E. Thailand growing alongside typical Cathaysian species (Rigby, 1998). Mixed flora is also documented along the Paleo-Tethyan margin of Gondwana during this time (Srivastava and Agnihotri, 2010). Furthermore, the discovery of the terrestrial *Dicynodon* fossil in Luangprabang, NW Laos, whose presence are also known in Laurussia, suggest at least a temporal terrestrial connection between Laurussia and the Sino-Vietnam-Indochina super-terrane during the Late Permian (Bercovici et al., 2012).

On a related note, several authors have attributed the Sam Nua arc (also known as the Song Ca arc) to the subduction of the Song Ma ocean (eg. Faure et al., 2016; Liu et al., 2012; Shi et al., 2015), which contradicts available geological data. Volcano-sedimentary deposits of the Sam Nua basin is represented by the Dong Trau Fm., resting unconformably on Carboniferous-Middle Permian carbonates. The formation's clastic components contain Anisian ammonoids such as *Amphipopanoceras* aff. *dzezinense*, *Paradanubites palmatus*, *P.* sp., *Leiophyllites* aff. *visendus* and *Paraceratites* sp. (Tran and Vu, 2011). The zircon U-Pb LA-ICP-MS ages of porphyritic dacite and porphyritic rhyolite are 245-229 Ma (Pham et al., 2015). These lines of evidence place the Dong Trau Fm. firmly in the Anisian (Middle Triassic), which post-dates the Song Ma resuturing event. No Late Permian-Early Triassic deposits are found in the Sam Nua basin. Also, based on the analysis of trace and rare-earth elements, the Dong Trau volcanic suite was probably derived from continental crust associated with the post-collision Sam Nua intra-continental rift.

After the Late Permian-Early Triassic mega-episode, the collision between Sibumasu and Sino-Vietnam-Indochina started from the Late Triassic, and was sometimes referred to as

the later stage of the Indosinian Orogeny (Fontaine and Workman, 1978; Helmcke, 1984; Sone and Metcalfe, 2008). More recently, the term “Cimmerian Orogeny” in the sense of Sengor (1988) was introduced for this event (Torsvik and Cocks, 2017, Wang et al 2018). However, following the initial pre-Late Triassic definition of the Indosinian orogeny, responsible for the collision between Indochina and Sino-Vietnam (S. China) blocks (Fromaget, 1941), the former term does not seem appropriate since the collision took place after the Late Triassic and involved two different continents, namely the Sibumasu and the Sino-Vietnam-Indochina composite terranes. Consequently, we propose the name Trans-Mekong orogeny for this suturing event, the final stage of which during the Jurassic formed mainland Southeast Asia (Charusiri et al., 2002; Metcalfe, 2013; Sone and Metcalfe, 2008).

6. Conclusion

Based on a comprehensive review of available geological data as well as new radiometric dating results, we recognized six major mega-episodes for the tectono-stratigraphic evolution of Indochina and adjacent areas during the Neoproterozoic to Early Triassic:

1) The Neoproterozoic-Early Cambrian mega-episode: Branches of the Proto-Tethys, including the Proto-Song Ma Ocean and the Tam Ky-Phuoc Son Ocean, separated the Sino-Vietnam (South China) and individual Indochina terranes. The Sino-Vietnam and Viet-Lao terranes then amalgamated during the Neoproterozoic or Early Cambrian.

2) The Middle Cambrian-Early Ordovician mega-episode: Shallow shelf carbonate deposition and the development of rich benthic faunas dominated north of the Proto-Song Ma suture, while in the south a deep marine and volcanic arc setting developed.

3) The Middle Ordovician-Silurian mega-episode: The Tam Ky-Phuoc Son Ocean subducted under the Viet-Lao, Viet-Cambodia and Kon Tum terrane, leading to the collision between these terranes along sutures around the Kon Tum terrane. This collision triggered the

Early Paleozoic intra-continental orogeny in the Sino-Vietnam composite terrane, and a unified Sino-Vietnam-Indochina super-terrane was established.

4) The Devonian-Tournaisian mega-episode: A passive continental shelf developed and marine transgression occurred over most of the study area, while the western Indochina margin was in an active setting. In some narrow troughs, deep water radiolarian chert were deposited on continental crust.

5) The Early Carboniferous (Visean)-Middle Permian mega-episode: The narrow Song Ma ocean reopened along the Proto-Song Ma suture, while widespread arc magmatism developed in western Indochina due to eastward subduction of the Paleo-Tethys.

6) The Late Permian-Early Triassic mega-episode: The Emeishan mantle plume triggered rifting in north Vietnam, and possibly crustal heating in the Kon Tum terrane in central Vietnam. The Sino-Vietnam and Indochina composite terranes collided again along the Song Ma suture. Contrary to popular beliefs, the “Sam Nua arc” postdates this collision.

The subsequent collision between Sibumasu and Indochina, here termed the Trans-Mekong orogeny, during the Late Triassic-Jurassic formed mainland Southeast Asia.

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Figure and Table captions

Figure 1. Paleozoic terrane map of Indochina and adjacent areas. Squared numbers indicate back arc suture: 1) Jinghong suture; 2) Nan-Uttaradit suture; 3) Loei suture; 4) Sra Kaeo suture. Circled numbers indicate metamorphic terranes: 1) Hoang Lien Son-Ailaoshan; 2) Phu Hoat; 3) Dian Cang; 4) Pailin. Numbers in ovals indicate massifs and complexes: 1) Nui Nua massif; 2) Nam Co complex; 3) Huoi Tong massif. Suture zones: ASSZ = Ailaoshan suture zone; BRSZ = Bentong-Raub suture zone; CRL = Chiang Rai Line; CMSZ = Changning-Menglian suture zone; CSSZ = Chu Sinh suture zone; PKSZ = Po Ko suture zone; SCSZ = Song Chay suture zone; SMSZ = Song Ma suture zone; TKPSSZ = Tam Ky-Phuoc Son suture zone. Faults: DBF = Dien Bien Phu Fault; MPF: Mae Ping Fault; SCF = Song Ca Fault; TDF = Thakhek-Da Nang Fault. Based on Tran and Vu (2011), Ren et al. (2013), Shu et al. (2014), Burrett et al. (2014), Rossignol et al. (2016), Metcalfe (2017), Faure et al. (2018).

Figure 2. Regional tectono-stratigraphic correlation of Indochina and the surround areas.

Figure 3. Stratigraphic correlation for the Neoproterozoic-Early Devonian in Vietnam. Modified from Tran and Vu (2011).

Figure 4. Cambrian rocks in North East Vietnam. A) Northwest-dipping monoclinical strata of medium-bedded marmorized limestone interbedded with meta-andesite of the Ha Giang Fm (ϵ_2); 10 km SSW to Bac Ha area, Lao Cai Prov. B) Monoclinical strata dipping $230 \angle 45$ of medium-bedded limestone-dolomite rhythmically interbedded with marlaceous shale containing Late Cambrian trilobites of the Chang Pung Formation.

Figure 5. Cambrian brachiopods and trilobites. 1. *Billingsella tonkiniana* Mansuy, external molds, Ha Giang, Chang Pung Fm, Late Cambrian, Geological Museum, Ha Noi; 2. *Calvinella walcotti* (Mansuy), Ha Giang, Chang Pung Fm, Late Cambrian, collection of Tran Huu Dan; 3. *Annamitia spinifera* (Mansuy), Penkai area, Yunnan, Ha Giang Fm, Middle Cambrian,

collection of Deprat J., 1915; 4. *Charchaqla norini* Troedsson, Ban Chau area, Thai Nguyen Prov., Than Sa Fm, Late Cambrian, collection of Pham Kim Ngan; 5. *Hedinasplis regalis* Troedsson, Ban Gioc area, Trung Khanh, Cao Bang Prov., Than Sa Fm, Late Cambrian, collection of Pham Dinh Long; 6. *Damesella brevlcaudata* Walcott, cephalon, Ha Giang Fm, Middle Cambrian, collection of Deprat J. 1915, Geological Museum, Ha Noi.

Figure 6. Examples of Late Ordovician-Early Silurian rocks in Indochina and the surrounding areas. A-C: Turbiditic deposits of the Co To Formation, NE Vietnam; D-F: Basal conglomerate of the Long Dai Formation, SW of Quang Binh Province, near Laos border. (A) Silt and shale interbedded with rippled fine-grained sandstone. (B) Cross-bedded sand with overlying slump deposits. (C) Small scale intra-formational fold and thrust, possibly related to slumping processes. (D), (E), (F): Middle Ordovician basal conglomerates yielding angular, semi-angular and semi-rounded boulders, pebbles and gravels.

Figure 7. Devonian-Carboniferous outcrops in Vietnam. (A) Cross-bedded sandstone and siltstone of the Do Son Group, Hai Phong City. (B) Stratigraphic boundary between Carboniferous and Devonian in the Pho Han Formation, South Cat Ba Island.

Figure 8. Distribution map of Carboniferous-Middle Permian and Late Permian-Triassic rocks. Exposed rocks are based on Ren et al. (2013), while subcrops are based on Booth and Sattayarak (2011) and Minezaki et al. (2019). Numbered basins: 1) Nanpanjiang basin; 2) Song Hien basin; 3) An Chau-Shiwandashan basin; 4) Tu Le basin; 5) Song Da basin; 6) Sam Nua basin; 7) Song Bung-An Khe basin.

Figure 9. Stratigraphic column of the study area for the Latest Devonian-Early Triassic. See Fig. 2 for legends.

Figure 10. Distributive features of chondrite-normalized REE and PM-normalized rare-trace elements of Early Permian igneous rocks (Tran T. A. et al., 2005). A, B: effusives of the Dak

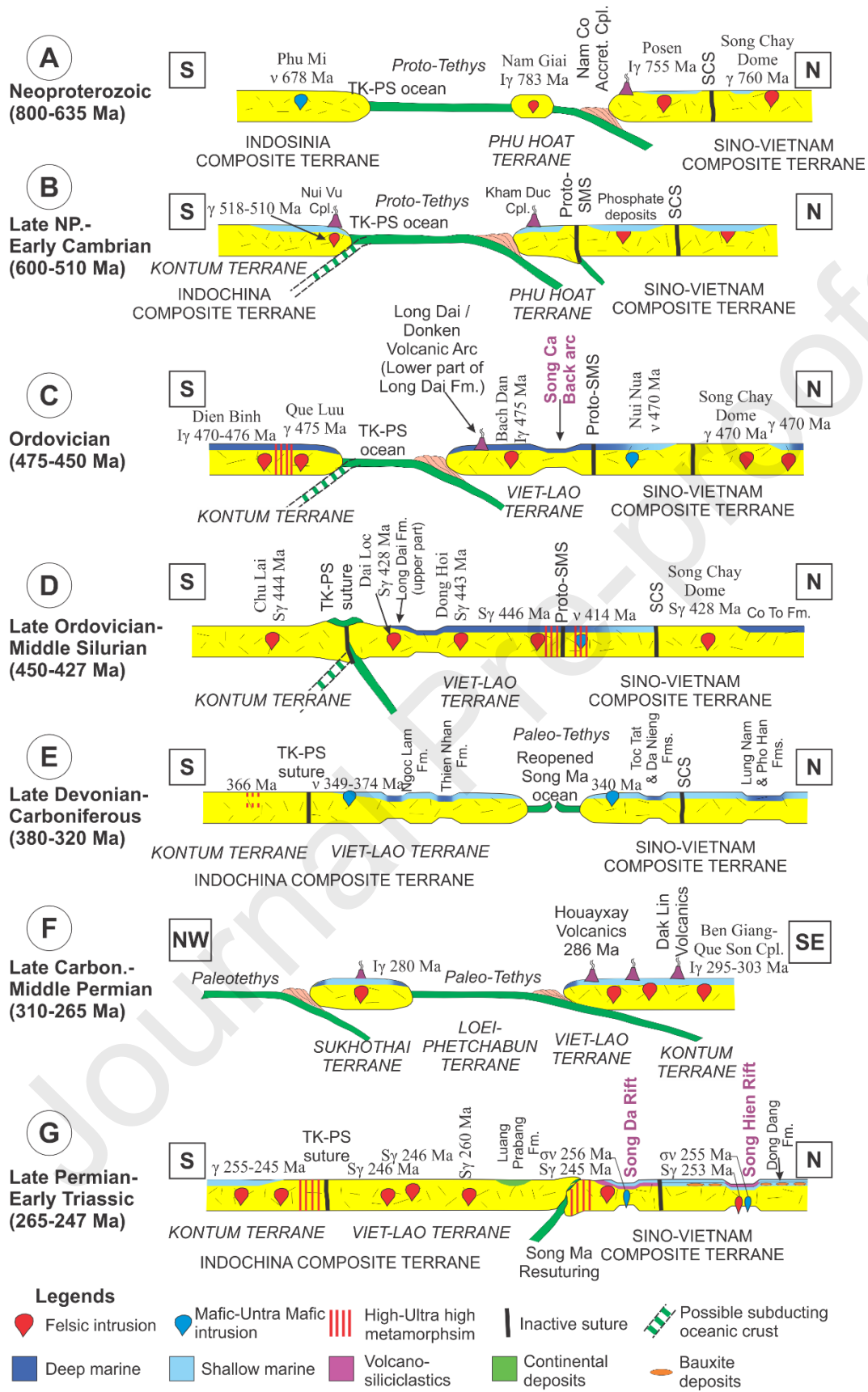
Lin Formation. C, D: effusives of the Chu Prong Formation. E, F: I-type granitoids of the Ben Giang-Que Son complex.

Figure 11. New zircon U-Pb LA-ICP-MS dating results for Paleozoic rocks in Indochina and adjacent areas.

Figure 12. Sketches of the Neoproterozoic to Early Triassic tectono-stratigraphic and geodynamic evolution of the study area. Prefixes of radiometric ages indicate rock types and affinities: γ : granite, v : mafic-ultramafic; I: I-type, S: S-type. SCS = Song Chay Suture; SMS = Song Ma Suture; TK-PS = Tam Ky-Phuoc Son.

Table 1: Location, GPS, lithology, analyzing lab and age dating results for 16 samples in Indochina and adjacent areas.

Graphical abstract



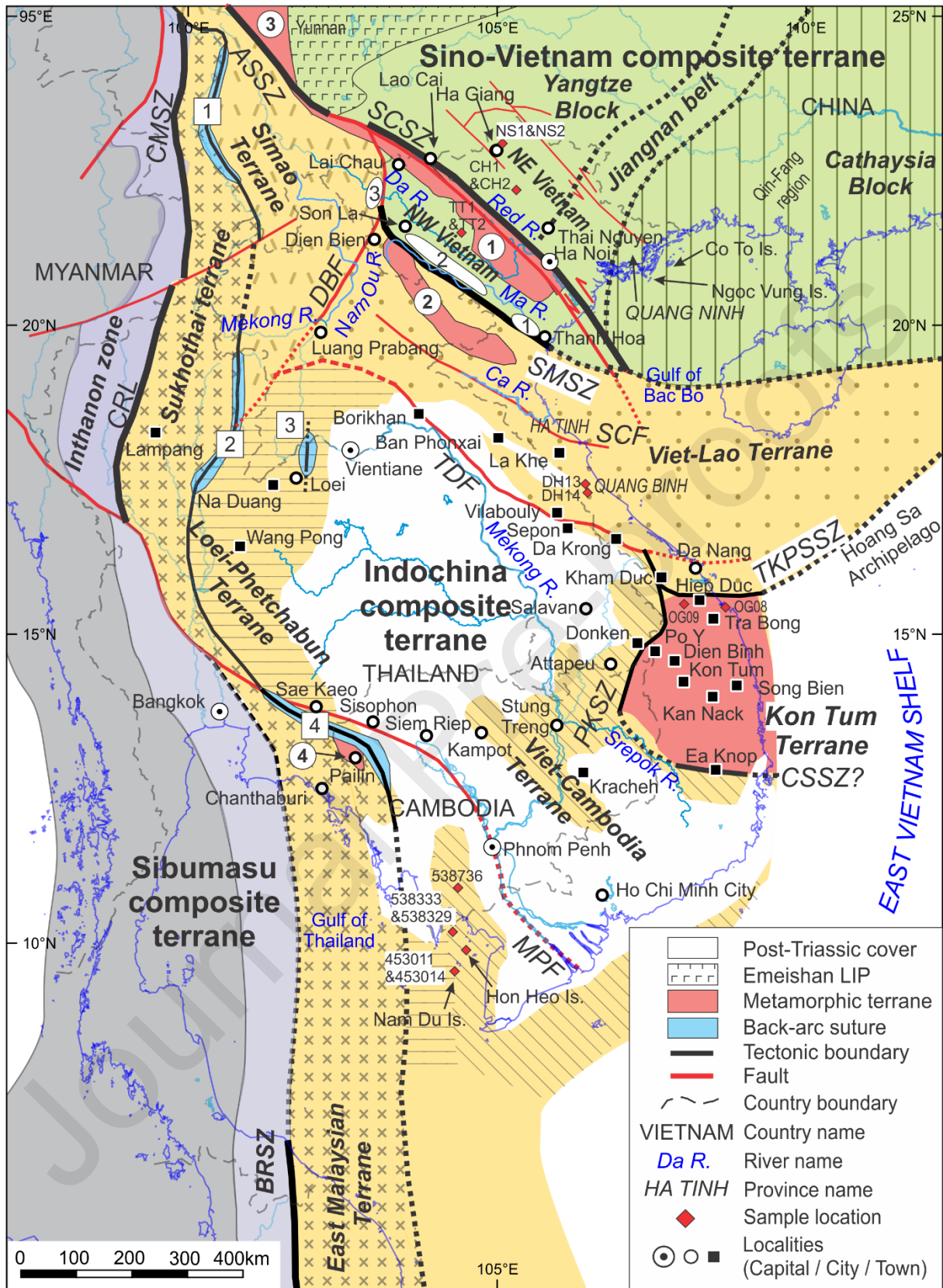
Highlights

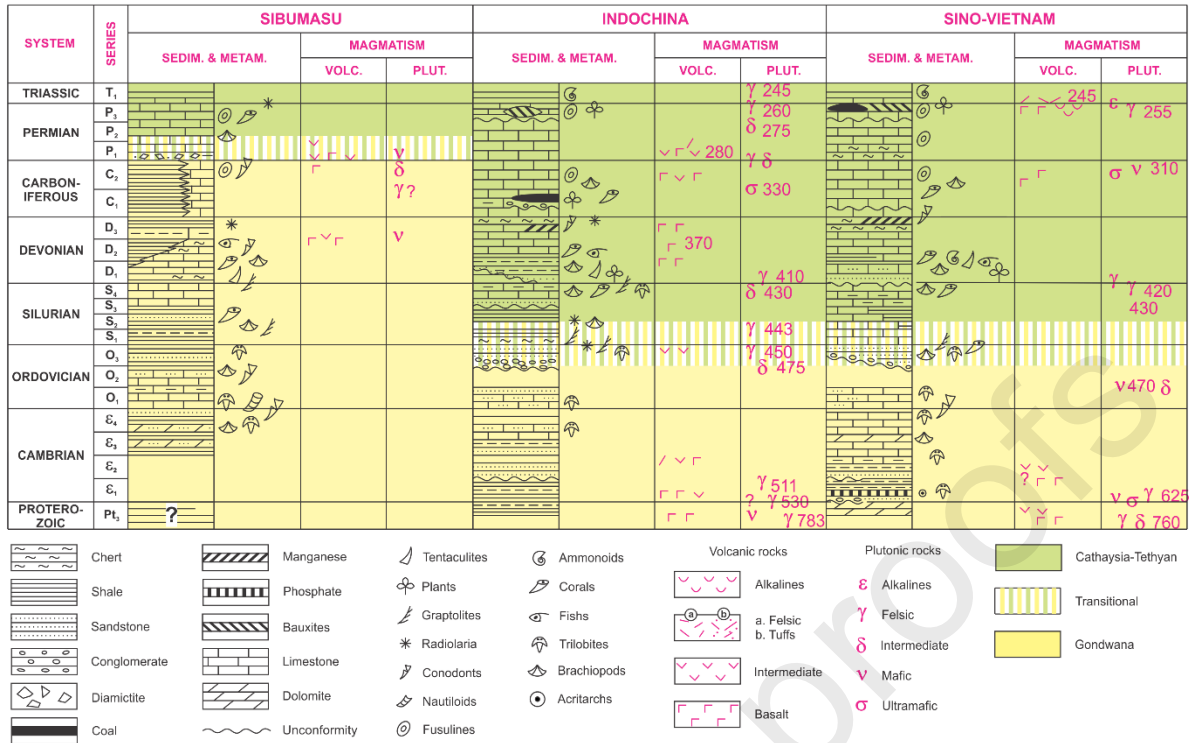
Neoproterozoic-Early Cambrian Proto-Song Ma suturing precedes Devonian-Carboniferous reopening

Middle Ordovician-Silurian collision formed a single Sino-Vietnam-Indochina landmass

Paleotethys subduction under Indochina caused Carboniferous-Middle Permian magmatism

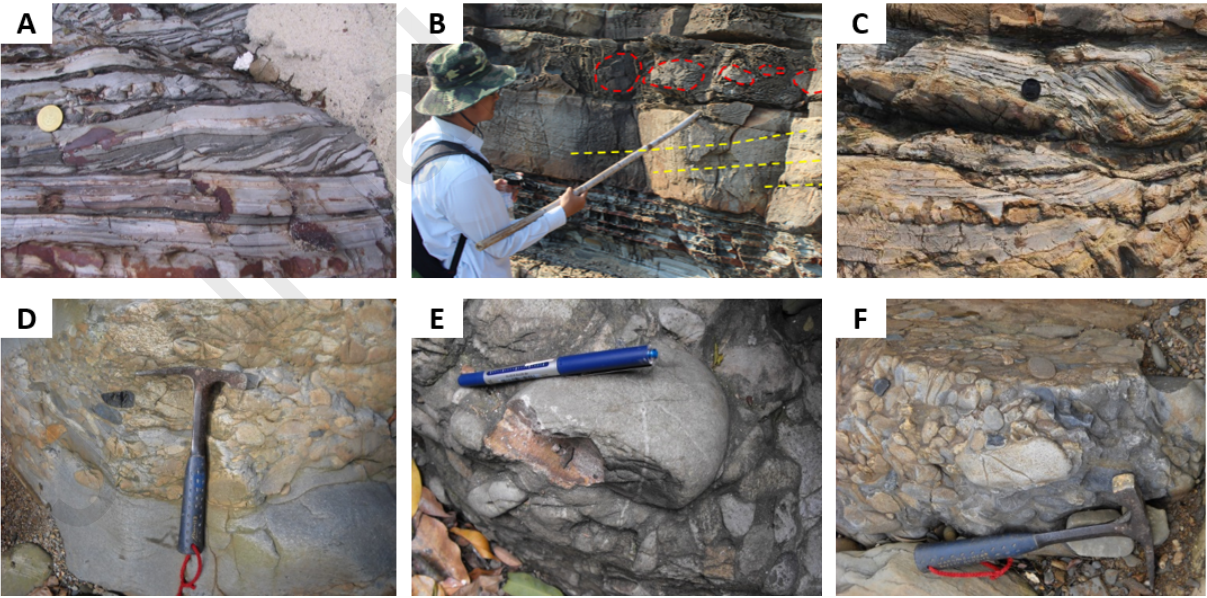
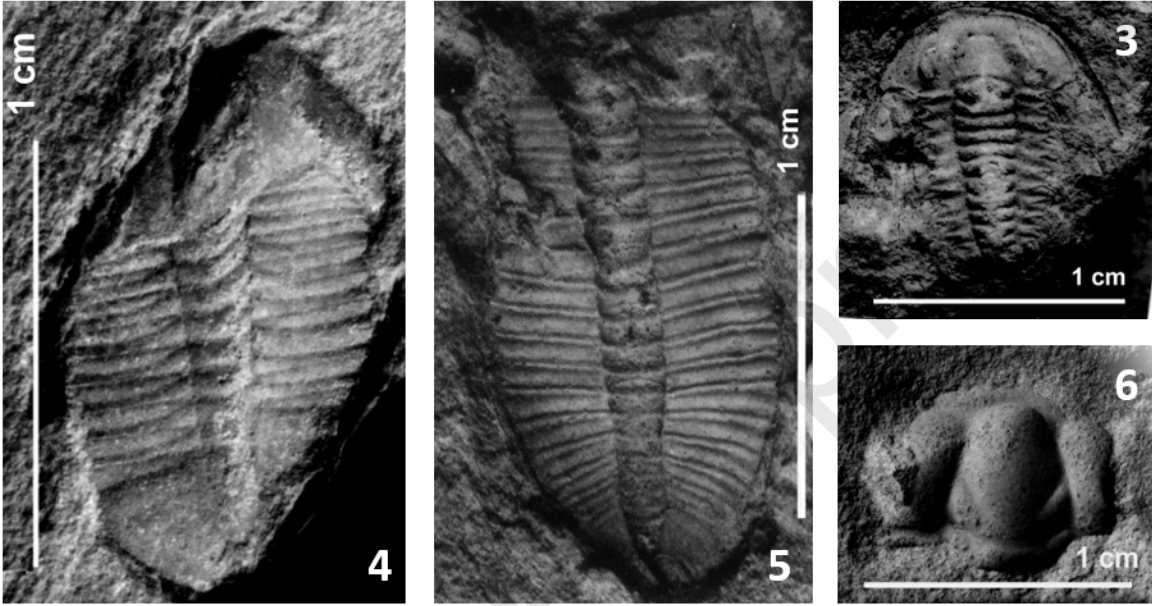
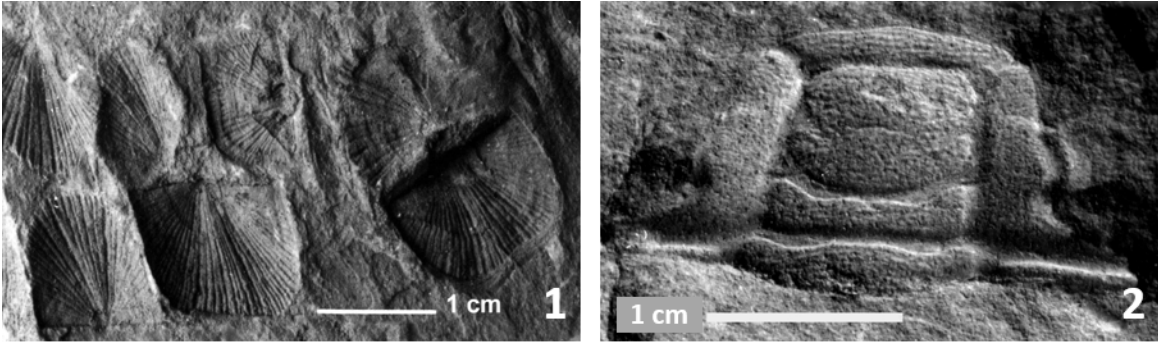
Indosinian resuturing along the Song Ma zone was coeval with plume-related rifting

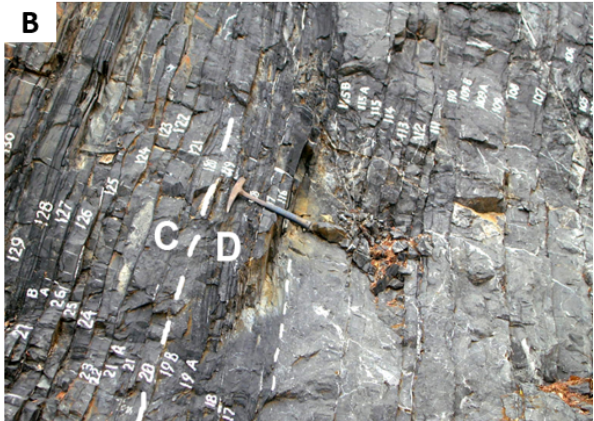




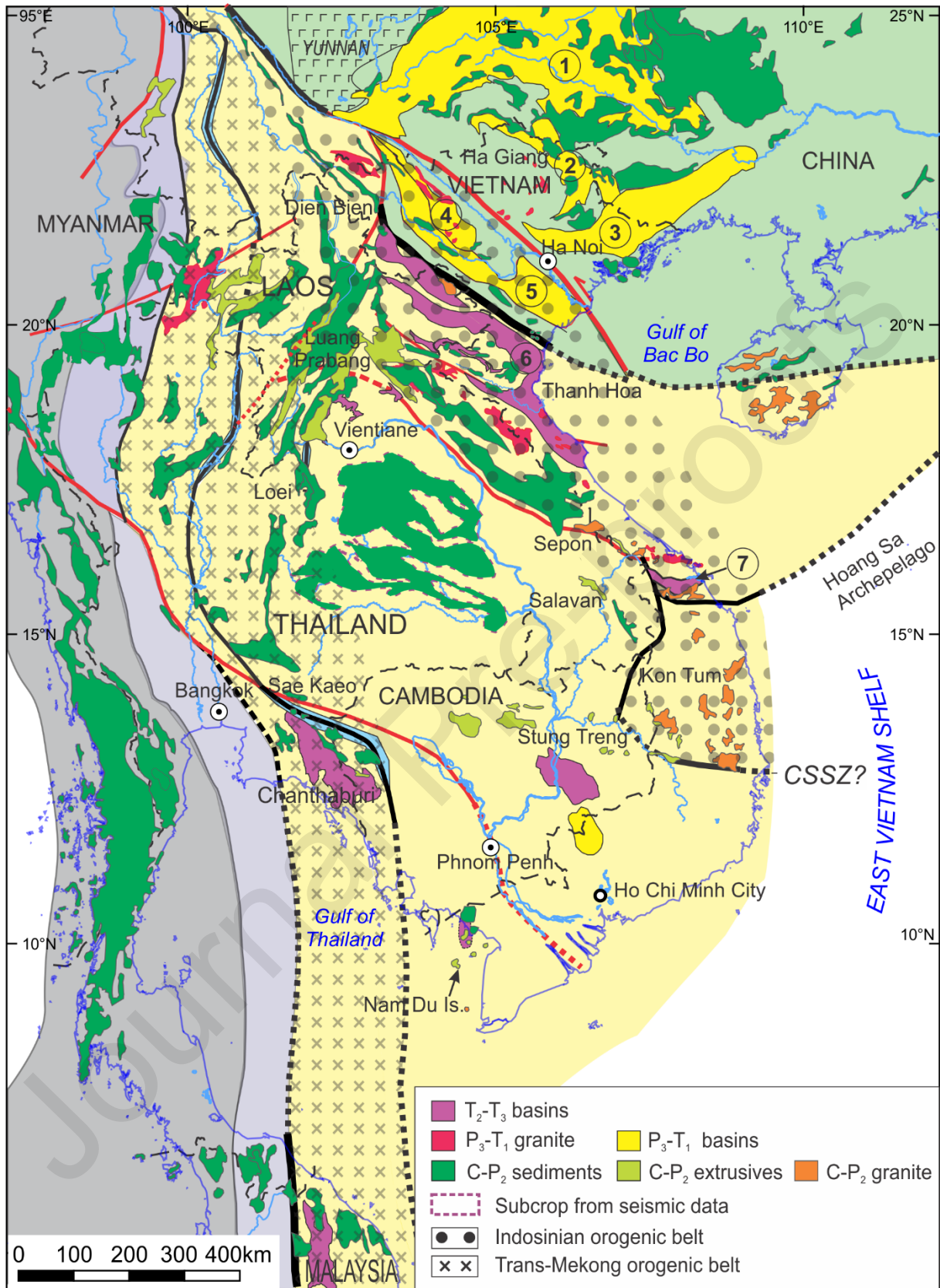
	Viet-Cambodia Terrane	Kon Tum Terrane	Viet-Lao Terrane		North Vietnam							
			South	North	NW Vietnam		NE Vietnam					
					SW part	NE part	NW part	SE part				
DEVONIAN	Hon Heo	Cu Brei	Tan Lam	Tay Trang	Nam Pia	Song Mua	Song Cau Gp.	Do Son Gp.				
SILURIAN	S ₄		Dai Giang		Ket Hay	Bo Hieng		Kien An				
	S ₃									Phu Ngu	Tan Mai	Co To
	S ₂											
ORDOVICIAN	O ₃	Phong Hanh	Long Dai	Song Ca	Dong Son	Sinh Vinh		Na Mo				
	O ₂											
CAMBRIAN	E ₄	A Vuong			Ham Rong	Ben Khe	Lutxia	Than Sa				
	E ₃						Chang Pung					
	E ₂						Ha Giang					
NEOPROTEROZOIC	E ₁	Nui Vu	Kham Duc	Suoi Mai	Nam Co	Cam Duong	Song Chay Gp.					
						Da Dinh	An Phu					
					Cha Pa		Thac Ba					







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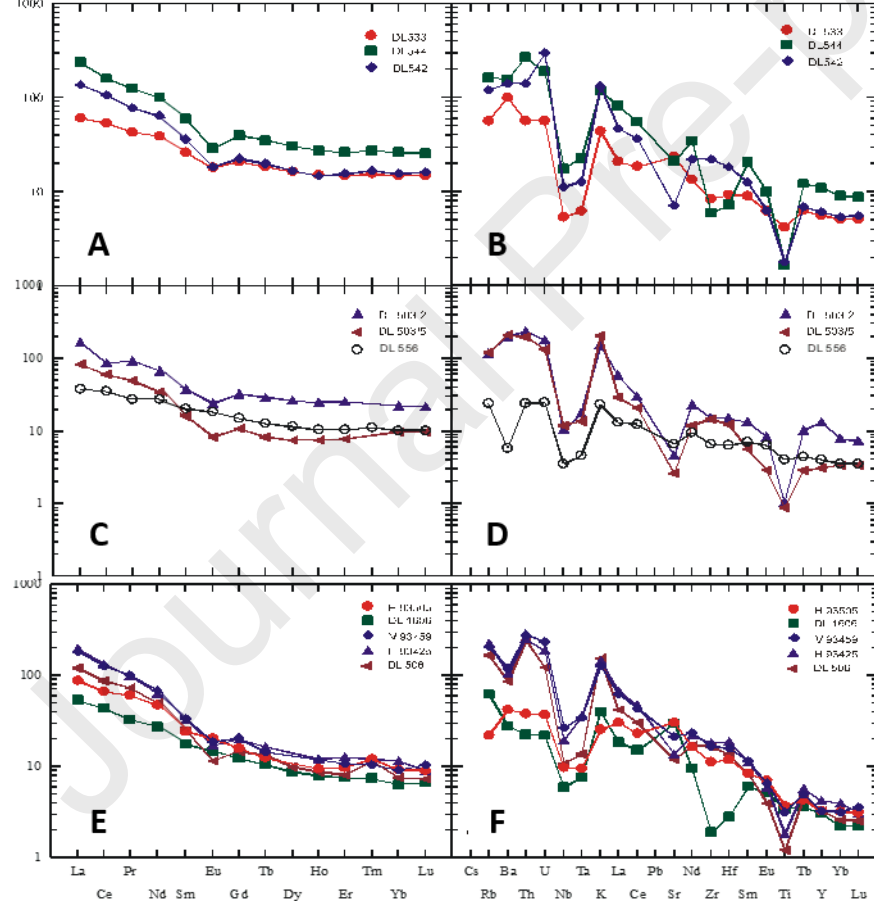


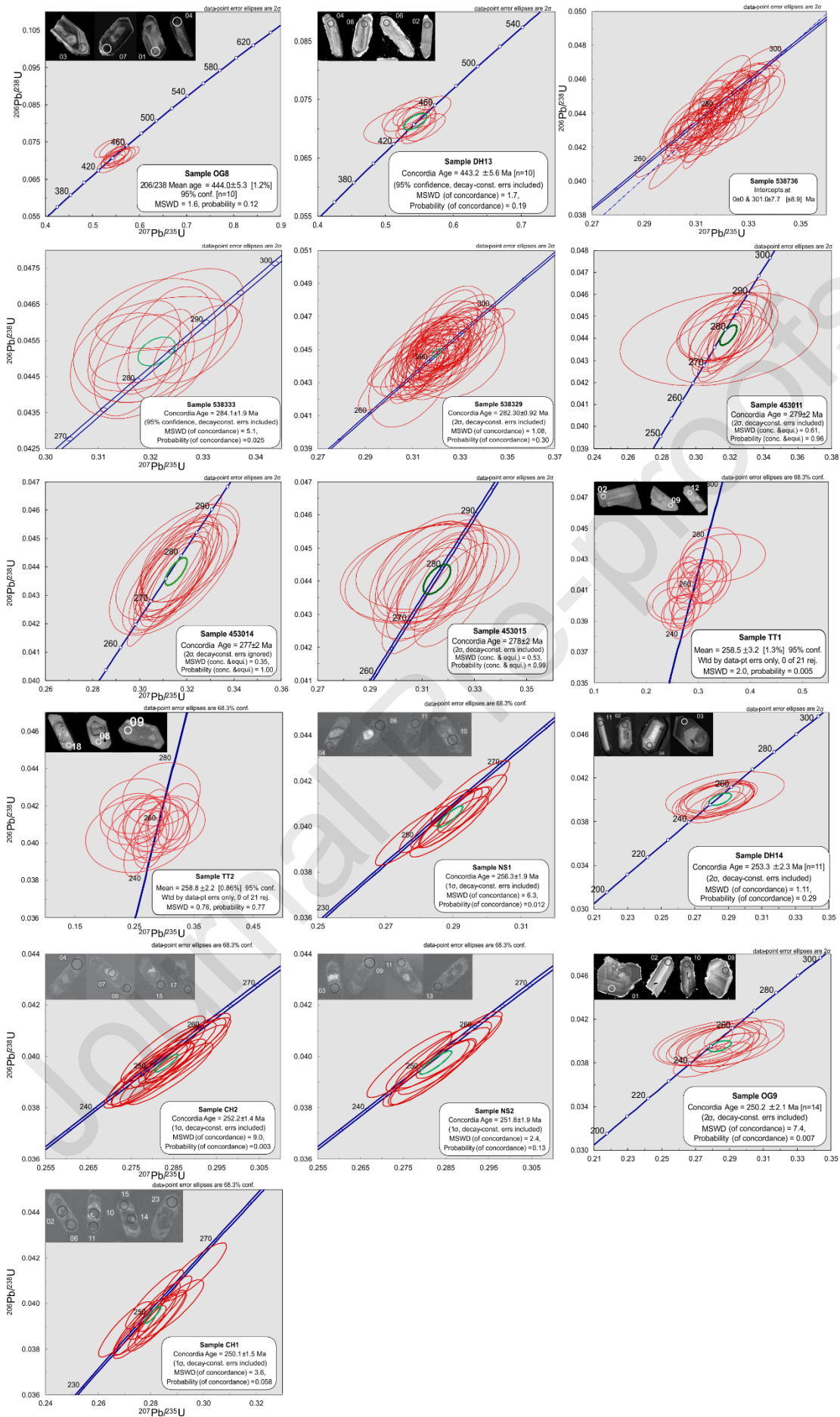
NW VIETNAM - LAOS - NE THAILAND

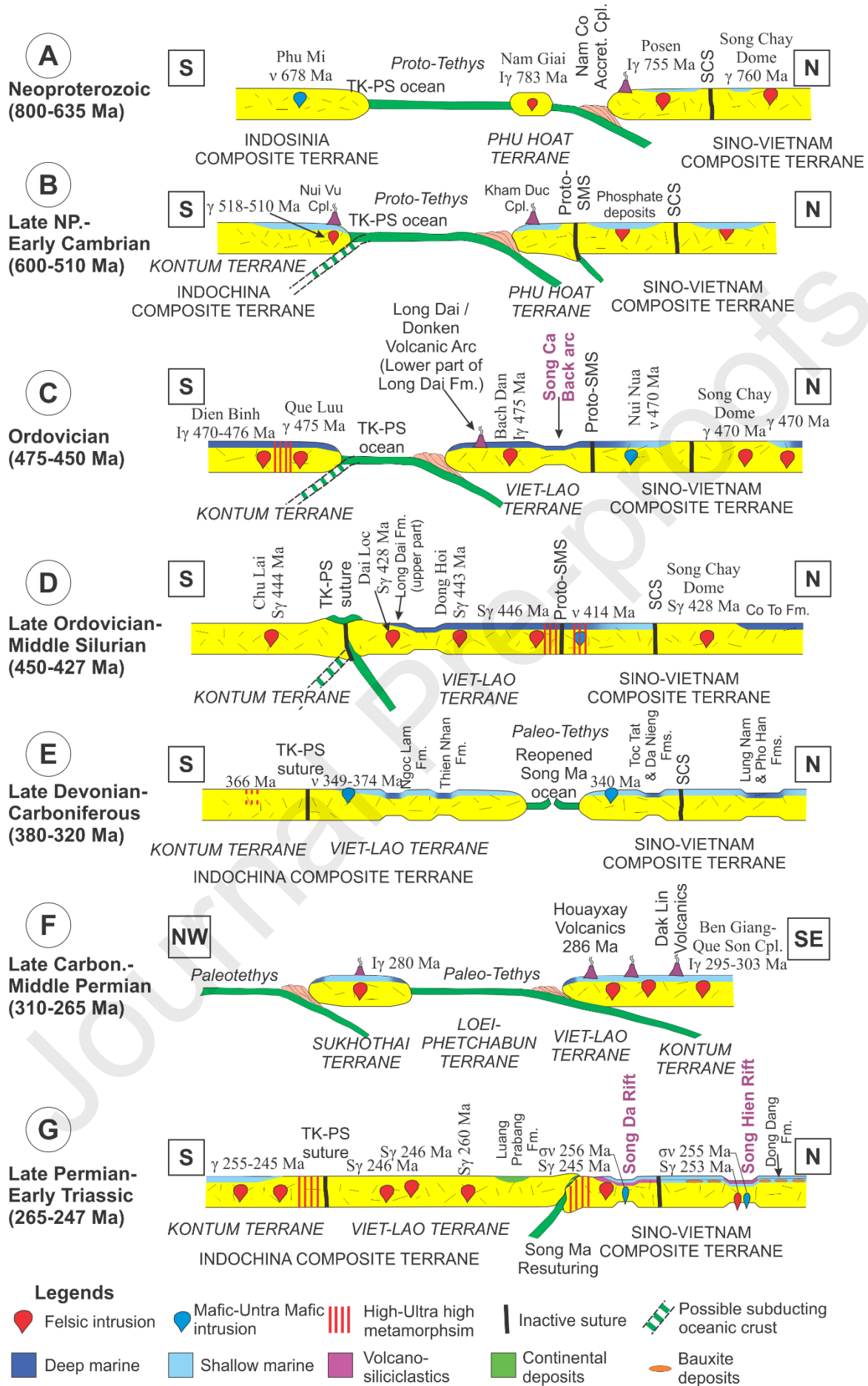
CENTRAL VIETNAM - SE LAO - NE CAMBODIA

ONSHORE AND OFFSHORE SOUTH VIETNAM - CAMBODIA

	STRAT UNIT	LITHOFACIES	THICKNESS (m)	DESCRIPTIONS	STRAT UNIT	LITHOFACIES	THICKNESS (m)	DESCRIPTIONS	STRAT UNIT	LITHOFACIES	THICKNESS (m)	DESCRIPTIONS					
PERMIAN	Lopingian	Co Noi	250	Tuffaceous sandstone, lenses of anthracite limestone. <i>Colanella parva</i> , <i>Palaefusulina</i> sp., <i>Nankinella indata</i> .	Cam Lo	250	Coaly shale contains forams <i>Taomopsis</i> sp., <i>Nanopsis</i> sp., <i>Pseudobulimina</i> sp., <i>Leptodus robitis</i> etc.	Song Sai Gon	Ta Viet	Ta Noi	750	Calcareous siltstone and sandstone: <i>Oreoceras</i> (<i>Melioseras</i>) <i>pinus</i> , <i>Opilionea</i> cf. <i>constricta</i> , <i>Chorata stocher</i> , <i>Arenolites</i> sp., <i>Palaekoumura</i> <i>prince</i> .					
		Yen Duyet	500	Porphyritic high-titanium basalt, ferruginous allo tuffaceous siltstone.							160	Conglomerates, sandstone, coaly shale: <i>Streptelasma</i> cf. <i>guyonensis</i> , <i>Grygoceras</i> sp., <i>Palaetina</i> sp.					
		Wuchapingian	280										300				
		Midian											240	Sandstone siltstone: <i>Halysites</i> sp., <i>Saetia</i> sp., <i>Compressirostratus</i> sp., <i>Cyrtolopos</i> sp.			
		Murgabian	1200 - 2300	Coaly shale siltstone: <i>Gigantopteris nicotinea</i> , <i>Pecopteris erudata</i> , <i>Carbonicola</i> , <i>Taomopsis multivaria</i> .													
	Gaudotian	Song Da	I-type granitoids: 272Ma		Siliceous shale, calcareous siltstone, bedded limestone: <i>Pseudoschwagerina</i> sp., <i>Pseudofusulina</i> sp., <i>Moscowia ovalis</i> , <i>Cancosina</i> sp., <i>Zelia</i> sp., <i>Productidae</i> etc. Cherty shale, mylonitic dacite interbedded with andesite, porphyritic mylonite, basalt. Gritstone, conglomerate, sandstone.	Dak Lin	550 - 900	I-type granitoids: 303-275Ma	Nem Du	Hi Thien	700	550	Rhyolite: 279 Ma	Thick bedded limestone: <i>Conostrophia</i> <i>Assemblage</i> , <i>Alphania</i> <i>Assemblage</i> , <i>Pentacrinus</i> cf. <i>astobus</i> . Dark gray bedded limestone: <i>Moscowia</i> <i>Assemblage</i> , <i>Pseudoschwagerina</i> , <i>Strophomena</i> <i>Assemblage</i> , <i>Pseudofusulina</i> <i>gracilis</i> etc. <i>Coras</i> , <i>Parawentidites</i> <i>regulus</i> , <i>Murchisonia</i> <i>constricta</i> etc.			
			Bolorian	272													
			Yakhtashian														
			Sakmarian	800 - 1300													
			Asselian	299													
CARBONIFEROUS	Pennsylvanian	Bac Son	>1200	Bedded limestone: <i>Eostaffella postmoscovensis</i> , <i>Pseudostaffella subquadrata</i> , <i>Endothyra amphialata</i> etc.	Bac Son	800 - 1000	Massive and thick-bedded limestone corals: <i>Rhynchophyllum</i> sp., <i>Koninkophyllum</i> sp., <i>Endothyra</i> sp., <i>Quasendothyra</i> sp., <i>Eostaffella</i> sp.	Hòn Heo	500	Siltstone interbedded with shale and sandstone.							
											Mississippian	Xóm Nua	Thôn Nhuan	800 - 1000	Conglomerate, sandstone, coaly shale, siliceous shale, anthracite: <i>Schizophoria</i> sp., <i>Gigantoproductus</i> sp., <i>Eostaffella</i> <i>konis</i> , <i>Vesicidictya</i> <i>kumekensis</i> , <i>Stigmaria rugiflora</i> , <i>Pecopteris aspera</i> , <i>Pleurophyllum grandis</i> , <i>Leptodermis</i> sp., <i>Medusa</i> sp., <i>Leptodermis oculifera</i> etc., <i>Asterella lutingaria</i> , <i>Aviculoplecton</i> cf. <i>dupontii</i> etc.		
																Tournaesian	359
	Viséan	323	Calcareous siltstone, coaly shale, sandstone containing plant fossils.	La Khe	800 - 1000												
								Serpukhovian	323								
	Bashkirian	323															
Moscovian						323											







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Table 1

No.	Sample ID	Place	Terrane	Latitude	Longitude	Rock type	Age	Analyzed by
1	OG08	Chu Lai quarry	Kon Tum	15° 24' 27"	108° 40' 55"	Granite migmatite	444.0±5.3 Ma	Kyushu Uni.
2	DH13	Dong Hoi	Viet-Laos	17° 27' 40"	106° 28' 02"	Granodiorite	443.2 ±5.6 Ma	Kyushu Uni.
3	538736	Phnom Knarng Takul	Viet-Cambodia	11° 01' 16.2"	104° 24' 12.2"	Granite	301.0±7.7 Ma	GEUS
4	538333	Hon Doc Isl. NE	Viet-Cambodia	10° 19' 15.9"	104° 19' 57.2"	Rhyolite	284.1 ±1.9 Ma	GEUS
5	538329	Hon Doc Isl. SE	Viet-Cambodia	10°19'17.4"	104° 20' 13.8"	Felsite	282.30 ±0.92 Ma	GEUS
6	453011	Nam Du Island	Viet-Cambodia	09° 40' 33.0"	104° 23' 58.0"	Rhyodacite	279±2 Ma	GEUS
7	453014	Nam Du Island	Viet-Cambodia	09° 41' 23"	104° 21' 05.0"	Rhyodacite	277±2 Ma	GEUS
8	453015	Hon Mau	Viet-Cambodia	10° 01' 20.0"	104° 32' 50.0"	Rhyolite	278±2 Ma	GEUS
9	TT2	Tram Tau, Yen Bai	North West Vietnam	21° 29' 00"	104° 24' 53"	Rhyolite	258.8 ±2.2 Ma	AIST
10	TT1	Tram Tau, Yen Bai	North West Vietnam	21° 29' 00"	104° 24' 53"	Rhyolite	258.5 ±3.2 Ma	AIST
11	NS1	Chiem Hoa-Na Son	North East Vietnam	22° 55' 35"	105° 04' 58"	quartz syenite	256.3 ±1.9 Ma	IESAS
12	DH14	Dong Hoi	Viet-Laos	17° 23' 27"	106° 28' 49"	Granite	253.3 ±2.3 Ma	Kyushu Uni.
13	CH2	Chiem Hoa-	North East Vietnam	22° 10' 27"	105° 18' 49"	Granite	252.2 ±1.4 Ma	IESAS

		Na Son						
14	NS2	Chie m Hoa- Na Son	North East Vietnam	22° 55' 17"	105° 05' 13"	quartz syenite	251.8 ±1.9 Ma	IESAS
15	OG09	Cha Val	Kon Tum	15° 38' 23"	107° 32' 43"	Gabbro	250.2 ±2.1 Ma	Kyushu Uni.
16	CH1	Chie m Hoa- Na Son	North East Vietnam	22° 10' 27"	105° 18' 49"	Granite	250.1 ±1.5 Ma	IESAS

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- Michel Faure: Methodology, Validation, Verification, Formal analysis, Investigation, Resources, Writing – Review & Editing
- Vuong Van Nguyen: Methodology, Formal analysis, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing
- Hoang Huy Bui: Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization
- Michael Bryld Wessel Fyhn: Investigation, Resources, Writing – Review & Editing
- Tuan Quang Nguyen: Investigation, Visualization
- Claude Lepvrier: Writing – Review & Editing
- Tonny B. Thomsen: Formal analysis, Resources
- Kenichiro Tani: Formal analysis, Resources
- Punya Charusiri: Writing – Review & Editing

Declaration of interests

We, the undersigned , declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Tran Van Tri