



From rifting to Indosinian orogeny recorded in the Indochina from late Devonian to late Triassic: A review

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ABSTRACT

The Indochina block, the most significant part of South East Asia, is bounded by the Ailaoshan-Song Ma suture zone in the north and Jinghong-Nan-Uttradit, Sra Kaeo suture in the west. These sutures result from the various tectonic events related to the rifting and closing of the Paleo-Tethys and successive collision of South China (Sino-Vietnam)-Indochina-Sukhothai arc-Sibumasu continental blocks. However, the timing of the commencement of the rifting eastern Paleo-Tethys, subduction, subsequent collision orogeny, duration of these stages, and their geodynamic mechanism remain controversial. Our review of the stratigraphic, sedimentary, magmatic, metamorphic, structural, and geochronological data available for the suture zones bounding and interior of the Indochina block indicate successive tectonic events from rifting through subduction to orogeny and provide new insights into the tectonic history from Late Devonian to Triassic that shape the Indochina block and its adjacent regions. The remnant of the Paleo-Tethys branch and deep marine cherts represented by the Ailaoshan-Song Ma and Nan-Uttradit suture melanges record the rifting and oceanic crust formation stage at ~380–313 Ma and 316–310 Ma, respectively. The southwestward subduction of the South China block under the Indochina block resulted in the development of the magmatic arc at ~310–247 Ma in the north Indochina block; meanwhile, the subduction of the Sibumasu block below the Indochina gave rise to the Sukhothai magmatic arc and Jinghong-Nan-Luang Prabang-Loei back-arc basins in the western Indochina at ~278–235 Ma. The South China slab rollback may significantly affect arc magmatism distribution in the north Indochina block. The final closure of the eastern Paleo-Tethys resulted in Indosinian collision orogeny of the Indochina with South China blocks at ~250–230 Ma in the Ailaoshan-Song Ma suture, followed by the Sibumasu block with Indochina-South China continent at ~240–230 Ma in the Jinghong-Nan-Uttradit-Sra Kaeo sutures. The late to post-collisional orogeny occurred in the north and west Indochina at ~235–200 Ma and ~230–200 Ma, respectively.

Keywords: Indochina block, Indosinian orogeny, Rifting, Ailaoshan-Song Ma suture, Truong Son belt.

1. Introduction

Precambrian South China (Sino-Vietnam), Indochina, and Sibumasu continental blocks,

which were rifted from the northern margin of the Gondwana and accreted one to another during the closure of Paleo-Tethys in the Triassic, formed the proto-South East Asia (Metcalf, 1988; 2013). Branches of Paleo-Tethys separated these blocks. The Paleo-

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Tethys is an ocean between the Cimmerian continent, a term first proposed by Şengör (Şengör et al., 2023), and the North China-South China-Indochina continent and extending from the Alps through Middle Asia, south Qiangtang to Yunnan and East Malaysia (Sone and Metcalfe, 2008; Metcalfe, 2013). The eastern side of this ocean is defined as the East Paleo-Tethys Ocean and consists of two branches. The first separates the South China block from North Qiangtang-Indochina. The second divides the Eastern Cimmerian continent and the Indochina block. Both

branches were closed in the Triassic, resulting in the accretion of these blocks (Sone and Metcalfe, 2008; Metcalfe, 2013; Burrett et al., 2014; 2021). The northern boundary between the Indochina and South China blocks corresponds to the Ailaoshan-Song Ma-Song Chay ophiolitic mélange zone (Lepvrier et al., 2008; Nakano et al., 2010; Faure et al., 2014; Tri et al., 2020). The Jinghong, Nan-Uttaradit, and Sra Kaeo sutures represent the western boundary between the Sukhothai magmatic arc and the Indochina block (Fig. 1).

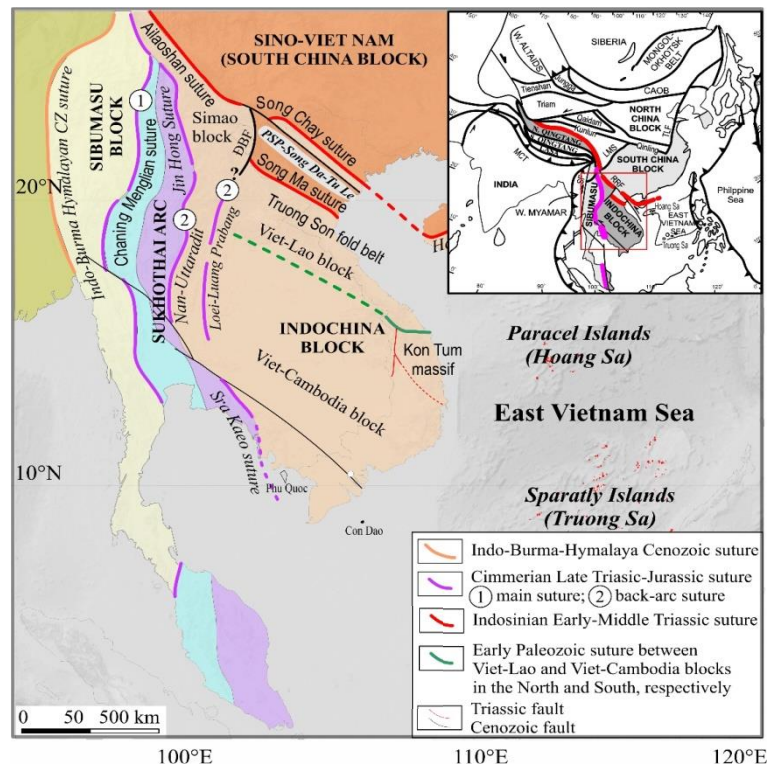


Figure 1. Tectonic sketch map of South East Asia with continental block and sutures Modified after Faure et al. (2017; 2018)

Although the sedimentary, stratigraphic, structural, magmatic, and metamorphic data have been accumulated from many places in Vietnam, Laos, Malaysia, southwest China, and Thailand over the past decades, the questions related to the timing of the rifting eastern Paleo-Tethys, subduction and subsequent collision orogeny, duration of the orogenesis and how these process work

remain in controversy. Some workers thought the collision between Indochina and South China was placed along the Dian-Qiong suture in southernmost South China (Cai and Zhang, 2009). However, most researchers consider the Ailaoshan-Song Ma suture to be the boundary between the Indochina and South China blocks (Tri et al., 1977; Lepvrier et al., 2008; Vượng et al., 2013; Zhang et al.,

2013; Faure et al., 2014; Wang et al., 2016; Faure et al., 2018; Tri et al., 2020). The collision timing between the Indochina and Sino-Vietnam blocks is also controversial. Some researchers suggested the pre-Devonian suturing based on the similarity of the sedimentary facies, stratigraphy, and fish fauna on both sides of the Song Ma suture zone (Thanh et al., 1996; Findlay and Trinh, 1997; Janvier et al., 1997). The others considered the suture to be dated in Triassic (Lepvrier et al., 2004; Nakano et al., 2008; Vượng et al., 2013; Faure et al., 2014; Zhang et al., 2014; 2016a; Anh et al., 2022a; Wang et al., 2022b) while Carter and Clift (2008) argue that the Song Ma suture is pre-Devonian and to be reactivated in Triassic. Some other authors propose the Indochina-South China amalgamation occurred in the Early Carboniferous (Helmcke, 1985; Metcalfe, 2013) based on the Visean terrigenous sequence of conglomerate, sandstone, shale, and coal layers containing *Peripteris* ferns fossils with Eurasian affinities. Whether the Indochina block or the South China one subducted under the other is also a matter of debate. Most researchers argue that the South China plate subducted under the Indochina block (Faure et al., 2016a; Wang et al., 2022b; Liu et al., 2023), while others argue that the Indochina plate subducted under the South China block (Lepvrier et al., 2008; Nakano et al., 2013). In this paper, we review and compile the available stratigraphic, magmatic, metamorphic, structural and geochronological data to discuss the tectonic evolution from rifting to subduction-collision leading to Indosinian orogeny of the Indochina block from the Late Devonian to Triassic.

2. Regional tectonic framework

2.1. General tectonic setting

The structural tectonic framework of the Indochina region results from a superimpose of the Cenozoic deformation on the Late Permian-Triassic structure. Cenozoic tectonics

characterized by ductile shear and strike-slip fault zones, among them the Ailaoshan-Red River sinistral ductile shearing plays an essential role in Oligocene-Miocene tectonics of southwest China and Southeast Asia. This shear zone extends over ~1000 km from the eastern Tibetan Plateau to the Gulf of Tonkin (Vietnam) and forms a lithospheric scale discontinuity separating the Indochina from South China blocks in the Cenozoic (Tapponnier et al., 1986; Leloup et al., 1995; Tapponnier et al., 1995; Yang et al., 2019). Based on the similarity of petrography, stratigraphy, geological structures, deformation kinematics, and age (Faure et al., 2014) documented that northeast and northwest fold belts in north Vietnam resulted from the same Indochina-South China blocks collision event along the Ailaoshan-Song Ma-Song Chay suture in Triassic. The Cenozoic sinistral Ailaoshan-Red River shear zone displaced the northwest part of Vietnam to the present position. Comparative research of Hf isotope and U-Pb age for detrital zircons in the ophiolitic mélange from the Ailaoshan, Song Ma, Song Chay segments supports this interpretation (Wang et al., 2021; Liu et al., 2023; Lin et al., 2024). The north-south trending Dien Bien fault bounded the Nam Po basin part of the Simao block is a brittle fault in the Oligocene (Bac et al., 2017). A Jurassic dextral movement along this fault zone is documented by the $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age of mylonite along this fault (Lin et al., 2009).

2.2. Late Permian-Triassic tectonic movement and the concept of Indosinian orogeny

Although strongly affected by Cenozoic deformation, the Late Permi-Triassic time is the most prominent tectonic period in Indochina. This tectonic event shaped the structure of a large region, including Vietnam, Laos, Cambodia, and Thailand. This Late Permian-Triassic tectonic movement is commonly named Indosinian orogeny in most

publications. The term Indosinian orogeny was used for the first time in north Vietnam by French geologists (Deprat, 1914a; Deprat, 1914b; Fromaget, 1927; Fromaget, 1934; Fromaget, 1941) who established a period of folding and thrusting after Carnian but before Norian continental red beds in the Song Da area. Afterward, the pre-Norian unconformity is well identified and recognized in northwest Vietnam, northeast Laos, the Truong Son belt (Fromaget, 1941), the Nong Son coal-bearing basin in northern Kontum massif, and the Khorat basin. In the Khorat basin, which covers a large part of Thailand and Laos, seismic profiles also indicate that the Permian sequence is folded and unconformably covered by the Late Triassic sequence (Minezaki et al., 2019). The tectonic event terminated at the end of Carnian, resulting in the Indosinian orogeny and the formation of a landmass named “Indosinia” (Fromaget, 1941). More and more works have been identifying Late Permian-Triassic magmatic, metamorphic, and deformation events in the Southeast Asia mainland, South China, Hainan Island, and South Korea and ascribed to Indosinian Orogeny (Kim and Ree, 2013; Faure et al., 2016b; Hara et al., 2024). However, in west Thailand, the Indosinian orogeny is divided into three events represented by three unconformities. The first unconformity between Anisian and Carinian ascribed to the Indosinian I event, the second at the base of Rhetian ascribed to Indosinian II, and the third at the base of Toarcian ascribed to Indosinian III (Helmcke and Lindenberg, 1983; Hahn, 1984; Hara et al., 2024). According to Hara et al. (2024), Indosinian I event is triggered by collision of Indochina-South China blocks, Indosinian II is caused by the collision between Sibumasu-Sukhoi Thai arc and Indochina blocks, Indosinian III is associated with post-collisional magmatism. Most researchers consider the Indosinian orogeny as result of collision of the Indochina-South China-

Sukhoi Thai arc-Sibumasu blocks when Paleo-Tethys closure along the suture zones that are presented in the following section.

2.3. Main suture zones

2.3.1. Northern boundary of the Indochina: the Ailaoshan-Song Ma-Song Chay suture zone

This suture extends over a thousand kilometers from southwest China to the Vietnam coast, likely continuing to Hainan island. The ultramafic-mafic and felsic bodies enclaved in the deep marine sedimentary matrix represent the ophiolite mélange. They are metamorphosed and now exhumed as narrow metamorphic belts along the Ailaoshan, Song Ma, and Song Chay belts (Lepvrier et al., 2008; Vượng et al., 2013; Faure et al., 2014; Zhang et al., 2014; Faure et al., 2016a; Tri et al., 2020; Wang et al., 2022b) (Figs. 1, 2).

The metamorphic complexes of the Ailaoshan, representing the northwest part of the suture, crop out in an NW-SE trending structural unit. In these high-grade metamorphic complexes, apart from Eocene-Oligocene metamorphic ages, high-pressure (HP) metamorphic mineral paragenesis of inclusions in paragneiss, amphibolite, and garnet-bearing pyroxenite still preserves well the 249–230 Ma U-Pb zircon ages (Liu et al., 2015a). The Ailaoshan suture is subdivided into three tectonic zones (Faure et al., 2016a). The western Ailaoshan in the Mojiang area is characterized by magmatic arc basalts and andesites dated at ~287–265 Ma (Fan et al., 2010). The diabase and plagioclase with NMORB geochemical affinity yield U-Pb SHRIMP ages of 382.9 ± 3.9 Ma and 375.9 ± 1.7 Ma and volcanic arc basalt dated 266.2 ± 2.2 Ma, respectively (Jian et al., 2009a). The central Ailaoshan represents a typical ophiolitic mélange in which serpentized ultramafic, gabbro, basalt, plagiogranite, chert, and limestone blocks are

enclosed in the siltstone matrix (Lai et al., 2014a). In the Jinping areas, eastern and similar to the Song Da formation in Ailaoshan, Late Permian basalt, pillow lava, northwestern Vietnam.

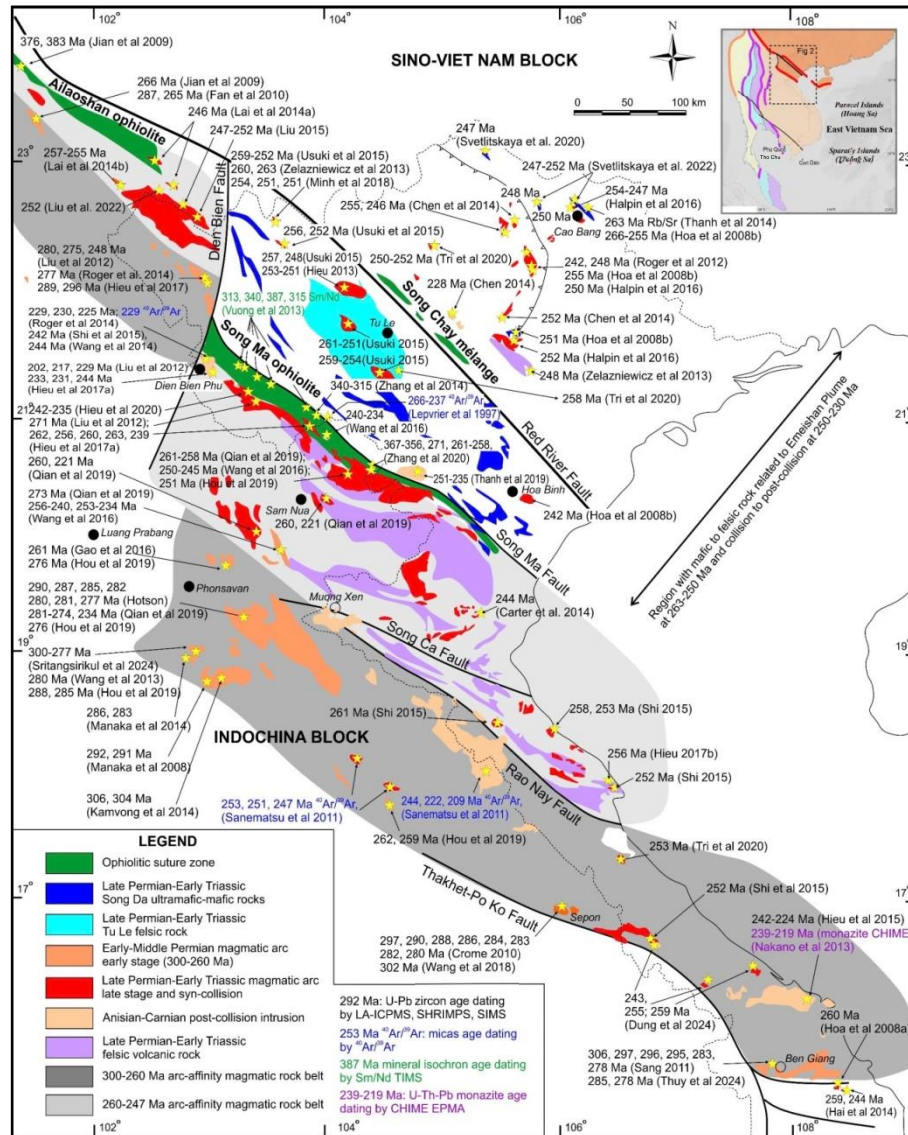


Figure 2. Distribution and age of Ailaoshan-Song Ma-Song Chay ophiolite and granitoid in Truong Son belt. Ages are from (Lepvrier et al., 1997; Carter et al., 2001; Hoa et al., 2008b; Manaka, 2008; Hotson, 2009; Jian et al., 2009b; Cromie, 2010; Fan et al., 2010; Liu et al., 2012; Hieu et al., 2013; Nakano et al., 2013; Vương et al., 2013; Wang et al., 2013; Żelazniewicz et al., 2013; Chen et al., 2014; Kamvong et al., 2014; Lai et al., 2014a; 2014b; Roger et al., 2014; Thanh et al., 2014; Tran et al., 2014; Zhang et al., 2014; Hieu et al., 2015; Liu et al., 2015b; Shi et al., 2015; Usuki et al., 2015; Gao et al., 2016; Halpin et al., 2016; Wang et al., 2016; Hieu, 2017; Hieu et al., 2017; Sang, 2017; Minh et al., 2018; Wang et al., 2018a; Hou et al., 2019; Thanh et al., 2019; Hieu et al., 2020; Tri et al., 2020; Zhang et al., 2020; Svetlitskaya et al., 2022; Dung et al., 2024; Sritangsirikul et al., 2024; Thuy et al., 2024). The detailed data are given in Table 1 in the supplementary file

The metabasalt, amphibolite and ultramafic blocks enclosed in the micaschist along the Song Ma suture segment are considered an ophiolitic mélange. In the Sam Nua area, (Zhang et al., 2020) found similar ophiolitic rocks.

The Song Chay suture was first proposed by (Dovjikov, 1965). It comprises gabbro, plagiogranite, and serpentinized ultramafic bodies and the blocks of Lower Paleozoic limestones, chert, and pelagic siliceous mudstones enclosed in a sheared sandstone-siltstone matrix (Lepvrier et al., 2011; Faure et al., 2014). The Song Chay suture was interpreted as a segment of the Ailaoshan-Song Chay-Song Ma suture zone laterally displaced by Cenozoic strike-slip tectonics (Faure et al., 2014; Faure et al., 2016a).

2.3.2. The western boundary of the Indochina

The western boundary of the Indochina with Sibumasu blocks comprises three tectonic suture zones from east to west: (1) the Luang Prabang-Loei back arc suture, (2) the Jinghong-Nan-Uttaradit-Sra Kaeo back arc suture, (3) The Changning-Menglian main suture (Fig. 1).

The Luang Prabang-Loei back arc suture

The Luang Prabang-Loei back arc suture extends from central Laos through Thailand. The pillow basalt and radiolarian-bearing thinly bedded chert are exposed along this zone (Wang et al., 2018b). The Carboniferous basalt-rhyolite (~350–310 Ma) and the Middle Triassic basalt-andesite (~240–238 Ma) in NW Laos and Phetchabun areas show MORB or arc affinity geochemical signatures (Qian et al., 2015) (Fig. 3).

The Jinghong-Nan-Uttaradite-Srakaao back arc suture

Jinghong suture segment comprises the

serpentinites, tholeiitic basalt, MORB-like Late Carboniferous-Permian basaltic andesite, and gabbro associated with deep marine radiolarian chert of Permian age (Metcalf, 2017) (Fig. 4).

The Nan-Uttaradit suture segment is a narrow N-S trending ophiolitic mélange zone of Carboniferous-Middle Triassic age (~316–240 Ma) in north Thailand (Fig. 4). The radiolarian chert in the suture is dated Anisian (Saesaengseerung et al., 2008). The Jurassic-Cretaceous continental sedimentary rocks overlain unconformably the suture (Metcalf, 2021).

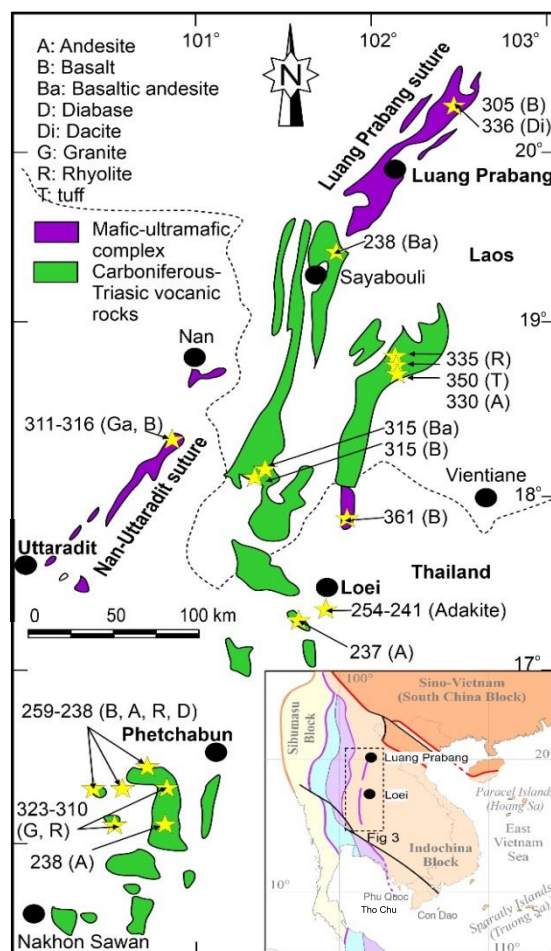


Figure 3. Distribution and age of magmatic rocks from Luang Prabang-Loei back arc suture (Modified after (Wang et al., 2018b))

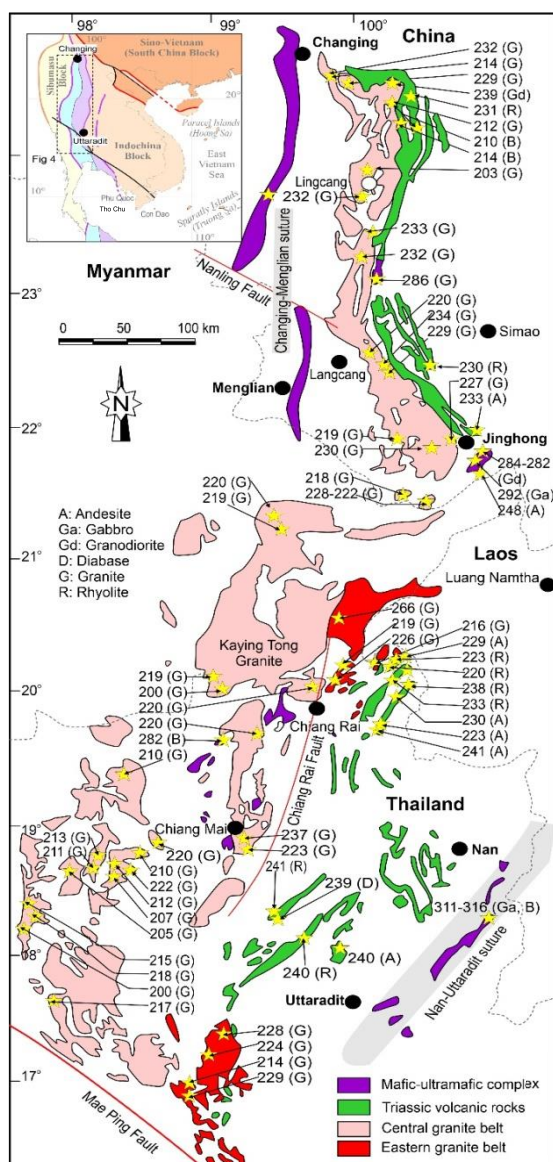


Figure 4. Distribution and age of magmatic rocks from east Sibumasu and Changning-Menglian suture (Modified after (Wang et al., 2018b))

The Sra Kaeo segment forms the boundary between the Chanthaburi terrain of the Sukhothai arc in the west and the Indochina block in the east (Metcalf, 2021). The suture mainly consists of serpentinite, gabbro, diabase, basalt, pillow basalt, limestone interbedded with sandstone, and shale. The Early Permian radiolarians and conodonts are discovered near Pailin, western Cambodia, in

the mélangé composing chert, basalt, volcanoclastic matrix, gabbro, serpentinite, and other places along this suture (Saesaengseerung et al., 2009; Udchachon et al., 2017). The amphibolite of the suture in the Pailin complex shows an N-MORB-like back-arc basin signature (Hara et al., 2020). The felsic dykes and plagiogranite of the complex yield U-Pb zircon ages between 283–275 Ma (Hara et al., 2020). The felsic rocks in the Nam Du archipelago of Vietnam yield similar U-Pb zircon ages between ~301–277 Ma (Tri et al., 2020). These rocks suggest the Sra Kaeo suture may continue in Vietnam's south of the Mekong Delta.

The Changning-Menglian suture zone

This zone welds the Sibumasu block with the Sukhothai arc of the Indochina block. It extends from southwest Yunnan in China through northwest Laos and northwest Thailand (Fig. 4). The Carboniferous-Permian (~340–260 Ma) mafic rocks in southwest Yunnan exhibit MORB geochemical affinity. The basalts in this zone commonly show geochemical characteristics similar to oceanic island basalt (OIB). They are directly overlain by the massive limestones containing Early Carboniferous-Permian fusulinids (Fan et al., 2015).

2.4. The main tectonic blocks

2.4.1. Indochina block

“Indochina” refers to a large region, including Vietnam, Lao, and Cambodia. The term Indochina block or composite terrane is used to include the reworked Precambrian metamorphosed block of Phu Hoat, Kon Tum, and possibly Pailin and Paleozoic Viet-Lao, Viet-Cambodia, Loei-Phetchabun, Simao, Sukhothai and East Malaysia blocks (Metcalf, 2013; Tri et al., 2020). The Indochina block consists of the Precambrian basement in the Kon Tum massif that has undergone at least two high-grade metamorphic events in Ordovician-Silurian

and Late Permian-Middle Triassic that correspond to Kwangsi in South China and Indosinian orogeny in Southeast Asia, respectively (Nam et al., 2001; Osanai et al., 2001; Lepvrier et al., 2004; Roger et al., 2007; Nakano et al., 2013; Nakano et al., 2021; Wang et al., 2022a; Xu et al., 2022). The Paleozoic and Mesozoic sequences are widespread in the Viet-Lao, Sukhothai arc, Loei-Phetchabun, and Simao blocks (Thanh et al., 2013; Zhao et al., 2017; Loydell et al., 2019). The upper Paleozoic-lower Triassic sedimentary sequences are characterized by shallow marine carbonate and siliciclastic

rocks. These rocks contain equatorial to tropical Cathaysian-type faunas and floras in the Sukhothai, Chanthaburi, and Loei areas (Metcalf, 2021) (Fig. 5). The Early Paleozoic, Late Carboniferous-Late Permian and Early-Middle ultramafic-mafic to felsic plutons intrude the Indochina block (Carter et al., 2001; Tâm et al., 2010; Kamvong et al., 2014; Shi et al., 2015; Pham et al., 2017; Hou et al., 2019; Qian et al., 2019; Hieu et al., 2020; Shang and Chen, 2022). The Late Triassic to Cretaceous red beds of the Khorat basin overly unconformably on the folded Late Paleozoic-Early Triassic sequences.

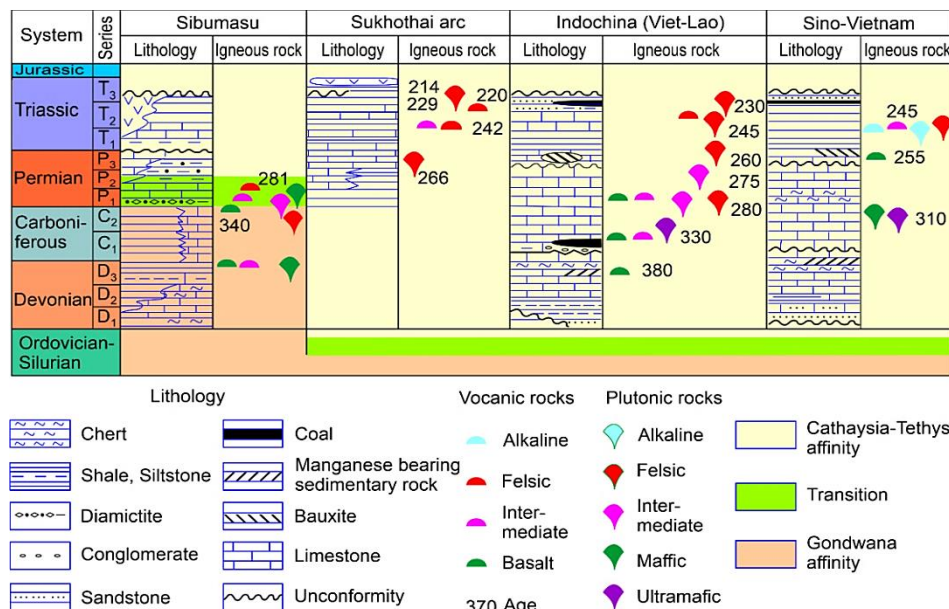


Figure 5. Geological characteristics of main tectonic blocks (Modified from Tri et al., 2020)

Before the Middle Devonian, the Indochina block is believed to have been connected to the South China block based on the similarity of the Silurian brachiopods and Early Devonian endemic faunas of South China. The Early Devonian flora remnants found in the islands of Bai Tu Long Bay (northeast Vietnam) are similar to those of the South China block (Gonez et al., 2012). The presence of Devonian freshwater fish fossils in the Truong Son belt and northeast Vietnam, including a Yunnanolepiform antiarch, which

is also known from the Yangtze terrane, indicates a continental connection with the Yangtze in the Early to Middle Devonian (Janvier et al., 1994; Thanh and Janvier, 1994; Thanh et al., 1996; Janvier et al., 2003). In this review, the Indochina block is viewed as a continental block united with the South China block after the collision orogeny between the Viet-Cambodia with Viet-Lao blocks in the Early Paleozoic (Usuki et al., 2009; Tran et al., 2014; Gardner et al., 2017; Faure et al., 2018; Wang et al., 2020a).

2.4.2. Sibumasu block

Sibumasu block extends from South Tibet-southwest Yunnan, Shan state of Burma, northwest Thailand, Peninsular Thailand, western Malaya to East Sumatra. It is also named the Shan-Thai block in Thailand or Baoshan-Tengchong in South West China (Metcalf, 1984; Bunopas et al., 2001; Xiaochi, 2002; Liu et al., 2009; Metcalfe, 2013). It comprises Precambrian to Late Mesozoic formations. The Cambrian-Early Ordovician sequence is represented by coarse grains of shallow marine sandstones and slates, which have changed to shallow marine carbonate and shale greywackes in the Ordovician. Deep marine graptolite-conodonts, fossiliferous black shales, sandstones, and chert represent the Silurian-Devonian. This sequence is unconformably overlain by the upper Carboniferous to Lower Permian glacial-marine diamictites and Middle-Upper Permian platform carbonates, similar to those in Northwest Australia (Ueno, 2003; Metcalfe, 2013; Wang et al., 2018b; Aung et al., 2024). These limestones contain a cold water Gondwana-type fauna that distinguished the warm water Cathaysia-type fauna of the Indochina block (Metcalf, 1984; Metcalfe, 1986). The Triassic intrusive plutons in this block are generated in two main intervals, ~242–235 Ma and ~231–213 Ma (Kanjapayont et al., 2020) (Fig. 5).

2.4.3. Sino-Vietnam block

The Sino-Vietnam or South China block resulted from the amalgamation of the Yangtze and Cathaysian blocks along the Jiangnan orogen. It occurred along the margin of Rodinia in the Neoproterozoic (Yao et al., 2019). Neoproterozoic-Early Paleozoic deposits unconformably overlie the Mesoproterozoic basement. Cambrian-Ordovician shallow marine fauna resembles those in Australia (Metcalf, 2013; Burrett et al., 2014). Late Ordovician-Early Silurian shelly faunas occur coevally in the Sibumasu block. Upper Paleozoic to Early Triassic sequences are characterized by shallow

marine siliclastic rocks with endemic Devonian faunas and Carboniferous-Permian warm-climate Cathaysian-type faunas and floras (Metcalf, 2013). In Guangxi, China, the Middle Devonian limestone is characterized by shallow marine with pelecypod faunas. In northeast Vietnam, the limestone and chert represent Carboniferous-Permian. An Upper Triassic-Lower Jurassic sequence unconformably overlies these Late Paleozoic to Early Triassic sequences. Early Paleozoic and Permo-Triassic tectonic events, namely Kwangsian and Indosinian events, are marked by anatectic granites dated ~460–400 and 250–220 Ma in eastern South China.

The detrital zircon age spectra of the Devonian sedimentary rocks from Sino-Vietnam, Indochina block, and Sibumasu show peak age at ~530, 950 and 1200 Ma for Sibumasu block and ~440, 965 Ma for Indochina and Sino-Vietnam block (Fig. 6).

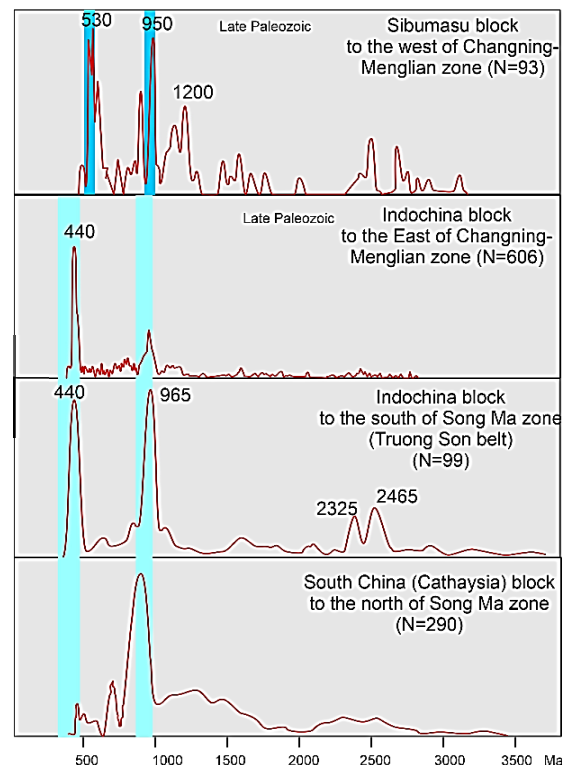


Figure 6. Detrital zircon age spectra pattern for Devonian sedimentary rocks from Sibumasu, Sino-Vietnam, and Indochina. Data sources are from (Wang et al., 2018b; Li et al., 2021)

3. Magmatic records

3.1. Late Devonian-Middle Carboniferous (~380–310 Ma)

Along the Ailaoshan-Song Ma sutures, the Late Devonian-Early Carboniferous oceanic magmatic rocks and deep marine sediments are found in several places. In the central Ailaoshan segment, plagiogranite from the Shuanggou area yields U-Pb zircon age ranging between ~383–376 Ma to 328 ± 16 Ma. The dolerite and plagiogranite collected from the same area also yield similar ages of ~364–334 Ma (Lai et al., 2014a).

In the Song Ma suture, the ultramafic-mafic rocks of the ophiolitic complex were dated between 387–313 Ma by Sm-Nd mineral isochron and U-Pb zircon (Vuong et al., 2013; Zhang et al., 2014). In the Sam Nua area in Laos, gabbro enclaves in plagioclase amphibolite yield similar 363–356 Ma U-Pb zircon ages. These gabbros have high positive $\epsilon_{\text{Nd}(t)}$, $\epsilon_{\text{Hf}(t)}$, and low $\delta^{18}\text{O}$ values indicating N-MORB-like geochemical affinity (Zhang et al., 2020).

Along the Song Chay suture segment, an ophiolitic mélange consisting of sporadic blocks of serpentinized ultramafic and mafic bodies, Lower Paleozoic limestone, chert, and siliceous mudstone enclosed in a sandstone-mudstone matrix exposed in the north of Day Nui Con Voi (Lepvrier et al., 2011; Faure et al., 2014). The depositional age of this mélange is partly constrained to approximately 310–254 Ma by detrital zircon from the ophiolitic mélange matrix (Wang et al., 2021).

3.2. Late Carboniferous-Middle Permian (310–260 Ma)

3.2.1. Northern Indochina

In northern Indochina, the Late Carboniferous-Middle Permian magmatism is widely distributed in two belts in the southern Song Ma suture, from Phonsavan to the north

of the Kon Tum massif. The Carboniferous-Middle Permian magmatic rocks comprise the Nam He-Muong Lay and Chieng Khuong plutons and equivalent plutons in Laos (Fig. 2). The gabbro-diorite to the granite in Nam He-Muong Lay, distributed to the west of the Dien Bien Phu fault and belonging to I-type granite, yields zircon U-Pb ages 296–289 Ma and 281–272 Ma, respectively (Liu et al., 2012; Roger et al., 2014; Hieu et al., 2017). The Chieng Khuong plagiogranite distributed along the Song Ma suture is dated 271–262 Ma age (Liu et al., 2012). The Chieng Khuong quartz-diorite is characterized by high Mg#, Cr, Ni, V, Rb, Th, U, La, and Nd contents and depleted in Ba, Nb, Ta, Sr, P, and Ti, high $^{87}\text{Sr}/^{86}\text{Sr}(i)$ and negative $\epsilon_{\text{Nd}(t)}$ value (Liu et al., 2012). The Nam He-Muong Lay granodiorite has a positive $\epsilon_{\text{Hf}(t)}$ value (Hieu et al., 2017). In the Phonxavan of north Laos, the 281–273 Ma U-Pb zircon-aged granitoid rocks are characterized by low $^{87}\text{Sr}/^{86}\text{Sr}(i)$, $\delta^{18}\text{O}$ and high Mg# values, positive $\epsilon_{\text{Nd}(t)}$ and $\epsilon_{\text{Hf}(t)}$ values, typical for I-type granite (Qian et al., 2019).

Southwestward Song Ma suture, in the Phu Kham to Sepon areas in Laos, the granodiorite to granites and associated volcanic rocks with zircon U-Pb ages of 306–270 Ma are characterized by the calc-alkaline, rich in Sr-Nd-Hf isotopic compositions and depletion in Nb and Ta, low HREE, high LREE contents and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, high Mg# number, positive $\epsilon_{\text{Hf}(t)}$ value (Cromie, 2010; Kamvong et al., 2014; Khin et al., 2014; Wang et al., 2018a).

In the southern Truong Son belt and northern Kon Tum massif, the gabbro, gabbro-diorite to hornblende-biotite granite of the Ben Giang complex are dated between 306–278 Ma (Sang, 2011; Thuy et al., 2024). They belong to high-K calc-alkaline series and metaluminous, enrichment in LILEs, and depletion of HFSEs (Tâm et al., 2010; Thuy et al., 2024). Although the U-Pb zircon ages of the Ben Giang complex are similar to those of

the Phu Kham and Sepon, their geochemical features are somewhat different. The Ben Giang gabbro to gabbro-diorite is characterized by low Cr, Co, and Ni content and a high ratio $^{87}\text{Sr}/^{86}\text{Sr}$, both negative $\varepsilon_{\text{Nd}(t)}$ and positive $\varepsilon_{\text{Hf}(t)}$. In contrast, its diorite and granodiorite phases are enriched in Sr-Nd isotopes, high Mg#, negative $\varepsilon_{\text{Nd}(t)}$. These geochemical features of the Late Carboniferous-Middle Permian magmatism suggest a continental magmatic arc setting developing southward of the Song Ma ophiolite suture.

3.2.2. Western Indochina

Compared to the north Indochina, the western magmatic rocks with geochemical affinity to the back-arc basin setting were formed between 316–255 Ma (Fig. 3). The gabbro from the Jinghong ophiolite complex yields U-Pb zircon ages of 298–293 Ma, indicating sea-floor spreading in the Early Permian (Zhu et al., 2021). In the Luang Prabang-Loei fold belt and northwest Laos, the basaltic and andesitic tuffaceous rocks yield Late Carboniferous zircon U-Pb ages 304 and 299 Ma and display both MORB-like and arc-like geochemical signatures (Shi et al., 2021b). The gabbro and meta-basalt in the Nan-Uttaradite suture yield U-Pb zircon ages of 311 ± 10 and 316 ± 3 Ma, respectively (Yang et al., 2016). The mafic rocks from the Nan and Luang Prabang zones give zircon U-Pb ages from 360 Ma to 265 Ma (Qian et al., 2016; Wang et al., 2020b).

In northwest Laos, the andesite and volcanic breccia hosted Au-Ag mineralization in the Ban Houayxai and Long Chieng Track dated 286–279 Ma (Manaka et al., 2014; Leaman et al., 2019). The breccia-bearing andesitic tuff in the B. On ultramafic complex yields a zircon U-Pb age of 260 ± 1.4 Ma, geochemically displaying a MORB-like signature. The andesitic tuff in the B. Kiophoulan-B. Houayhak belt gave the U-Pb age of 254 ± 1.3 Ma, with arc-like geochemical affinity (Shi et al., 2021a).

3.3. Late Permian-Early Triassic (260–247 Ma)

The magmatic rocks with ages 260–247 Ma occur in three regions: (i) in the Song Da-Tu Le; (ii) in the vicinity of the Song Ma suture; (iii) in the Kon Tum massif.

In the Song Da-Tu Le zone, the 262–249 Ma U-Pb zircon ages are recorded in the Tu Le rhyolite (262–249 Ma), the Muong Hum and Phan Si Pan hypabyssal plutons (~257 Ma), the Song Da high- and low-Ti volcanic and volcano-plutonic ultramafic-mafic associations (~260 Ma) (Fig. 2). These rocks are ascribed to Emeishan intraplate large igneous province offset in the Cenozoic by the left strike-slip Red River shear zone (Balykin et al., 2010; Usuki et al., 2015; Shellnutt et al., 2020).

Immediately southward of the Song Ma suture, the porphyritic biotite and biotite-hornblende granite in the first phase of the Song Ma complex are formed in this period. Meanwhile, the porphyritic granodiorite and quartz-diorite in the second phase are emplaced slightly later. These rocks are closely related to the Middle Triassic volcano-sedimentary sequence of marine facies. The coal-bearing upper Triassic terrestrial sedimentary sequence unconformably covering two complexes and metamorphic rocks can be observed in eastern Dien Bien Phu, Dien Bien Dong, and Sop Cop. The porphyritic biotite hornblende granite of the Song Ma complex yields ~263–256 Ma zircon U-Pb age (Hieu et al., 2017). The Song Ma granites are characterized by low Mg content and metaluminous, negative Nb, Ta, P, and Ti anomalies, and they are rich in high-field strength elements (Hieu et al., 2017). The Sam Nua and Muong Lat granites yield similar zircon U-Pb ages between 261–247 Ma (Qian et al., 2019; Thanh et al., 2019). The volcano-plutonic complexes in Ha Tinh, Quang Binh, and Quang Tri are crystallized between 261–242 Ma (Shi et al., 2015; Tri et al., 2020).

In the southern Truong Son, the Cha Val complex, consisting of diorite and granodiorite, is distributed mainly in the south Truong Son belts and north Kon Tum massif. They belong to I-type and metaluminous, medium to high K and rich in Cs, U, Pb, Nd, depletion in Ba, Nb, Ta, P, Eu, and Ti, high $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ value, negative whole-rock $\varepsilon_{\text{Nd}(t)}$. The zircon U-Pb ages indicate their emplacement between 258–249 Ma (Minh et al., 2021).

3.4. Middle-Triassic (247–230)

The Middle Triassic granitic plutons are widespread in the Truong Son belt and western Indochina block (Figs. 2–4).

In the Song Ma zone, the Dien Bien complex consists of calc-alkaline plutons with a composition from mafic to felsic. These intrusions are formed in three phases, corresponding to gabbro-diorite and diorite in the early phase, quartz-diorite and granodiorite in the intermediate phase, and granite in the late phase. The gabbro-diorite to the granite of the Dien Bien complex yields ages between 233–217 Ma (Liu et al., 2012; Roger et al., 2014; Hieu et al., 2017). The published geochemical and isotope data indicate their inhomogeneity for different rock types. The Dien Bien pluton belongs to metaluminous with high K, relatively high $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$, and negative $\varepsilon_{\text{Nd}(t)}$ (Liu et al., 2012; Anh et al., 2022b). The quartz monzonite and porphyritic granodiorite of the complex are characterized by calc-alkaline to high-K calc-alkaline and peraluminous type with relatively high Mg#, rich in LREEs and depleted in Ba, Nb, Ta, P, and Ti (Liu et al., 2012).

The Hai Van and Ba Na complex is mainly distributed in the southern Truong Son belt. The Hai Van pluton, the most extensive intrusion, is a batholite body extending in the E-W direction in the southern Truong Son belt. These granites belong to S-type, medium-high-K, calc-alkaline peraluminous granites with 242–220 Ma zircon and

monazite U-Pb age (Hoa et al., 2008a; Nakano et al., 2013; Hieu et al., 2015). They are depleted in Ba, Ta, Nb, Ti, P, and Sr and rich in LILEs (Hieu et al., 2015). Most of the research interpreted the Hai Van complex to be formed from the partial melting of crustal rocks in a syn-collision or post-collisional setting in the Middle-Late Triassic (Hoa et al., 2008a; Hieu et al., 2015; Tri et al., 2020).

3.5. Late Triassic (230–200 Ma)

The Late Triassic magmatism develops mainly west of the Indochina block and forms the central and western belt (Fig. 4). These granites belong to two micas, high K granite, and are mainly classified as S-type granite, with some as I-type granite. They are formed in a post-collisional setting of Sibumasu with Indochina (Jiang et al., 2021).

4. Metamorphic records

4.1. The Ailaoshan-Song Ma suture

Metamorphic data play a crucial role in understanding the evolution of orogenesis. The pressure-temperature-time-deformation records are helpful in the identification of the tectonic process that affected the crust and lithosphere. Subduction to collisional orogenic process usually generates high-pressure (HP) metamorphic facies of oceanic, continental crust during subduction. Therefore, the high-pressure rocks are considered to be indicative of the subduction-collision zone. In the Ailaoshan-Song Ma suture, the ages of HP eclogite metamorphic facies rocks are consistent between 249–230 Ma (Nakano et al., 2008; Nakano et al., 2010; Liu et al., 2013; Zhang et al., 2013; Xuexiang et al., 2018). The pressure-temperature (P-T) conditions of the eclogites along the Song Ma suture indicate clockwise metamorphism evolved from amphibolite facies (14–16 Kbar and 520–550°C) through eclogite facies (24–27 Kbar and 650–750°C) and termination by retrograde stage of amphibolite to greenschist facies at 3–7 Kbar and 430–510°C (Zhang et al., 2013) (Fig. 7).

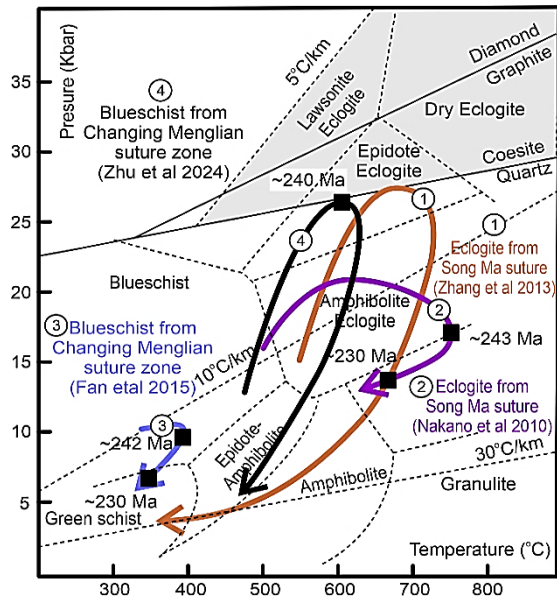


Figure 7. P-T-t path of high-grade metamorphic rocks from the Song Ma, Changning-Menglian suture zones. Data sources are from (Nakano et al., 2010; Zhang et al., 2013; Fan et al., 2015; Zhou et al., 2024). The subdivisions of eclogite (EC) of amphibole eclogite (Amp-EC), epidote eclogite (Ep-EC), lawsonite eclogite (Lws-EC), and dry eclogite are also indicated (after Maruyama et al., 1996)

The metasedimentary rocks of the Nam Co complex surrounding the ophiolite mélange and Ta Khoa antiform yielded U-Pb SHRIMP monazite metamorphic age of 234 ± 10 Ma (Hau et al., 2018) and 247–240 Ma on the zircon and monazite SHRIMP U-Pb dating, respectively (Wang et al., 2023). These ages are similar to syn-kinematic micas ages ~251–229 Ma and clustering on 245 Ma (Lepvrier et al., 1997; Lepvrier et al., 2004). These data indicate that the Song Ma eclogite was metamorphosed at the HP condition of the subduction zone with a low thermal gradient of $\sim 8^\circ\text{C}/\text{km}$ in the Early-Middle Triassic time (Zhang et al., 2013).

4.2. The Changning-Menglian suture

In the western boundary of Indochina, some geochronological data indicate the metamorphic age is 210–200 Ma, younger than that of the Ailaoshan-Song Ma (Ahrendt et al., 1993; Macdonald et al., 2010). The Late Triassic metamorphic condition is estimated at 6–7 Kbar and $600\text{--}700^\circ\text{C}$ for the Doi Inthanon area (Macdonald et al., 2010). Lenticular blueschists with a formation age of ~ 260 Ma are preserved in the Suyi-Ankang and Huiming areas (Fan et al., 2015). These blueschists have mineral paragenesis of zoned glaucophane, albite, epidote, phengite, and chlorite. This assemblage records an isothermal decompression P-T-t path from ~ 9 Kbar at ~ 242 Ma to ~ 6 Kbar at ~ 230 Ma within the temperature range from 300°C to 450°C (Fan et al., 2015). Recent research in north Lancang shows eclogite's metamorphic age between 245–227 Ma by Lu-Hf, Sm-Nd, and U-Pb methods (Zhou et al., 2024). These eclogites record a clockwise P-T-t path from blueschist-facies conditions at ~ 14 Kbar and $\sim 520^\circ\text{C}$ to peak eclogite-facies conditions at ~ 25 Kbar and $\sim 600^\circ\text{C}$ at 240 Ma, followed by decompression to amphibolite facies at $< \sim 7$ Kbar (Zhou et al., 2024).

5. Structure and tectonic kinematic records

5.1. Northeastward overthrust in North Vietnam-South China

In North Vietnam-South China, structural investigations in the different complexes and syn-kinematic micas obtained from the Song Ma suture to Song Hien and the southern margin of the South China block are valuable indicators (Lepvrier et al., 2011; Lin et al., 2011; Chen et al., 2014; Faure et al., 2014;

Faure et al., 2016b; Wang et al., 2021; Wang et al., 2022b). Those structural data allow us to understand better how the collision and late to post-collision orogeny between the Indochina and South China blocks evolve. All the kinematic data from the macro to microscopic scales indicated consistently a tectonic transportation top to the north-northeast during the Middle Triassic to form the nappe structure and north-east vergence folding with the $^{40}\text{Ar}/^{39}\text{Ar}$ age of syn-kinematic muscovite at 245–240 Ma (Faure et al., 2014; Wang et al., 2022b). This top to the north-northeast kinematics indicates the southward subduction of the Sino-Vietnam block below the Indochina block and subsequent deformation.

5.2. Ductile Strike slips in the Truong Son fold belt

In the Truong Son belt, from the Song Ma suture to the Tam Ky-Phuoc Son suture, several Middle Triassic highly strained NW-SE to E-W strike-slip dextral shear zones are documented at ~245–230 Ma by syn-kinematic micas (Lepvrier et al., 1997; Lepvrier et al., 2004; Lepvrier et al., 2008). The dextral shearing, coeval with upright folding, overprinted on the previously folded Paleozoic sequence unconformably covered by Lower Devonian sandstone.

6. Process from rifting to collision and Indosinian orogeny

6.1. Rifting and spreading

The identification of ~380–310 Ma ophiolitic rocks with N-MORB affinity and highly positive $\varepsilon_{\text{Nd}(t)}$ (+3.3 to +10.7) and $\varepsilon_{\text{Hf}(t)}$ (+6.68 to +7.41) and low $\delta^{18}\text{O}$ values (5.3‰–5.5‰) along the Ailaoshan-Song Ma-Song Chay (Vuong et al., 2013; Zhang et al., 2020) indicate that oceanic crust was formed from the Late Devonian to Middle

Carboniferous. The Carboniferous sediments associated with the ophiolitic in the central Ailaoshan are dominated by a black shale-sandy limestone-limestone sequence (Lai et al., 2014a). Southward Song Ma suture, the Carboniferous sedimentary rocks of the La Khe formation are also dominated by black-grey shale, coaly shale, cherty shale, and cherty limestone and are likely correlated to those in the central Ailaoshan segment. These sedimentary rocks indicate an oceanic depositional environment, with progressively increasing depth toward abyssal, continued after the breakup of the passive margin. However, the Early-Middle Carboniferous flora-bearing conglomerate, coal seam, and carbonate shale in the Saravan coal mine in Laos overlies unconformably the older formation (Tri et al., 2020). This feature indicates the shallower depositional environment to the south. These data of deep marine sedimentary rocks associated with serpentized ultra-mafic rocks evidenced that the Ailaoshan-Song Ma oceanic crust was generated in the Late Devonian-Early Carboniferous. The Ailaoshan-Song Ma Ocean separates the South China and Indochina blocks and forms a branch of Paleo-Tethys (Metcalf, 2021).

In the western boundary of the Indochina block, the mafic to felsic rocks with geochemical affinity to MORB and magmatic arc were formed between 316–255 Ma, corresponding to Middle Carboniferous to Late Permian (Fig. 8). In association with deep marine chert-bearing Permian to Middle Triassic radiolaria, these rocks were formed in the deep marine environment in the Jinghong-Nan-Uttaradit and Luang Prabang Loei back-arc setting as evidenced by geochemical data (Shi et al., 2021b).

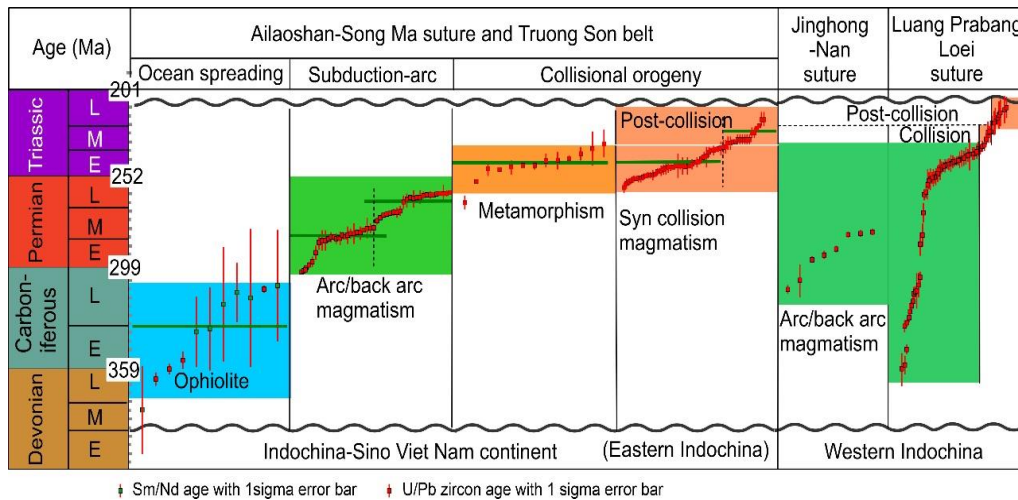


Figure 8. Synthetic magmatic and metamorphic ages for the Ailaoshan-Song Ma, Truong Son belt, Jinghong-Nan, Luang Prabang-Loei sutures, and tectonic setting. Data are from (Lepvrier et al., 1997; Hoa et al., 2008b; Manaka, 2008; Hotson, 2009; Jian et al., 2009b; Cromie, 2010; Fan et al., 2010; Liu et al., 2012; Hieu et al., 2013; Nakano et al., 2013; Vuong et al., 2013; Wang et al., 2013; Żelaźniewicz et al., 2013; Chen et al., 2014; Kamvong et al., 2014; Lai et al., 2014a; 2014b; Roger et al., 2014; Thanh et al., 2014; Tran et al., 2014; Zhang et al., 2014; Hieu et al., 2015; Liu et al., 2015b; Shi et al., 2015; Usuki et al., 2015; Halpin et al., 2016; Wang et al., 2016; Hieu, 2017; Hieu et al., 2017; Sang, 2017; Minh et al., 2018; Wang et al., 2018a; Wang et al., 2018b; Hou et al., 2019; Thanh et al., 2019; Hieu et al., 2020; Tri et al., 2020; Zhang et al., 2020; Dung et al., 2024; Sritangsirikul et al., 2024; Thuy et al., 2024)

6.2. Subduction-arc setting

The transition from a passive margin to a subduction zone plays an essential role in the evolution of an ocean. It marks the shift from the extensional regime associated with the forming oceanic crust to the compressional regime related to developing the subduction-arc magmatic system, usually leading to mountain belts. However, how and when such a transition occurs is a challenging issue. In the subduction setting, magmatic rocks were generated mainly when one slab was subducted under the other to produce a magmatic arc. Therefore, the oldest age of the magmatic rocks with the geochemical affinity to those formed in the magmatic arc setting is used to deduce the minimum age of the subduction. The oldest gabbro-granodiorite with arc affinity in the Truong Son belt is dated ~306 Ma (Wang et al., 2018a). Therefore, it is deduced that the subduction of

the Sino-Vietnam below the Indochina block started after 313 Ma (the youngest age of the ophiolite member) and before 306 Ma (the oldest age of arc affinity granodiorite). The shift from a passive margin environment to a subduction setting is likely marked by the unconformity of the La Khe and Bac Son formation in both the Sino-Vietnam and Indochina blocks (Tran and Vu, 2011). The timing of ~310 Ma, corresponding to the Moscovian, seems reasonable for initiating the subduction in northern Indochina.

This subduction gave rise to a magmatic arc in northern Indochina parallel to the subduction zone. These plutons are characterized by I-type granite with high Mg#, calc-alkaline, and K and belong to the metaluminous series. Their geochemical signatures show an enrichment of LREEs and LILEs compared to HREEs, HFSEs, and negative Eu anomalies. The $\epsilon_{\text{Nd}(t)}$ and $\epsilon_{\text{Hf}(t)}$

values are almost positive, with some negative values for the more and younger age felsic phase of intrusion. These values also show a progressively reduced tendency for old to young intrusions (Hoa et al., 2008a; Cromie, 2010; Liu et al., 2012; Kamvong et al., 2014; Hieu et al., 2017; Qian et al., 2019; Anh et al., 2022a; Thuy et al., 2024). All these geochemical signatures are typical for subduction-related arc magmatism and evidence for developing the subduction-arc setting in the northern Indochina block. In the western Indochina boundary, the andesite with magmatic arc affinity is formed between 286–240 Ma. Therefore, the magmatic arc environment was developed in the Late Carboniferous-Early Triassic.

6.3. Termination of subduction-arc setting and collision-orogeny

The question of when the collision between Sino-Vietnam and Indochina blocks initiates is somewhat difficult to precise if based only on the magmatic data. Temporally, the magmatism evolves continuously from the subduction through collision to the post-collision setting. Geochemically, the igneous rocks, generated from the compression of the subduction-collision orogeny to the extension of the post-collision orogenic tectonics, are more and more enrichment of the crustal materials. Furthermore, during the evolution of the subduction-collision-orogeny to post-collision, the differentiation, mixing, mingling, and assimilation can alter the composition of the primary magma, generating the compositional variability of igneous rocks. However, the collisional orogeny is associated with metamorphism and changes in detrital zircon provenance. Therefore, the formation ages of HP eclogite facies rocks along the Ailaoshan-Song Ma suture zone provide reasonable constraints for

the transition from subduction to collision. The ages of eclogite metamorphic facies rocks are consistent between 249–230 Ma (Nakano et al., 2008; Nakano et al., 2010; Liu et al., 2013; Zhang et al., 2013; Xuexiang et al., 2018). A comparison of detrital zircon isotope composition for the western Ailaoshan and Truong Son belts indicates a magmatic quiescent between 270–265 Ma. After this period, the magmatic arc develops again between 260–250 Ma (Li et al., 2021). This period overlaps with the onset of ELIP in the north of the Ailaoshan belt between 265 and 250 Ma. Therefore, a reasonable age accounting for the ending of subduction along the Ailaoshan-Song Ma zone is after ~260 Ma and before 249 Ma, the timing of eclogite. Hence, the subduction of the Sino-Vietnam block below the Indochina block should end after ~260 but before ~250 Ma to start collision to generate eclogite at ~249–247 Ma recorded in the Ailaoshan and Song Ma suture. This collisional orogeny lasts until ~230 Ma, as evidenced by the age of the retrograde path of HP metamorphic rocks and the ending ductile deformation.

Based on these arguments, the collision is likely from ~250 to 230 Ma. Consequently, the 250–230 Ma magmatic rocks in the Truong Son belt are considered syn-collision, and the magmatism postdated ~230 Ma corresponds to post-collision. Some plutons with crystallization ages between 247–242 in the Truong Son belt have arc affinity geochemical features (Wang et al., 2016). This time interval overlaps the metamorphic and deformation age, but mismatch with geochemical features can be explained by a diachronous collision and or by the input of mantle materials to the crust of the overriding plate during the early phase of the collision.

The 233–217 Ma Dien Bien and 240–220 Ma Hai Van granites are characterized by calc-alkaline to high-K calc-alkaline, peraluminous type with relatively high Mg#, rich in LREEs and depleted in Ba, Nb, Ta, P, and Ti and high negative $\varepsilon_{\text{Hf}(t)}$ value. These features resemble well with post-collisional geochemical characteristics. However, a successive overlap in the magmatic ages between the arc setting with syn-collision to post-collision environments indicates a continuous evolution from the subduction to post-collision (Fig. 8).

In the Sukhothai arc, available data indicate a switch from subduction of the Paleotethyan Ocean to the collision of the Sibumasu with Indochina blocks at ~237 Ma with subsequent syn- and post-collisional events at ~237–230 Ma and ~230–200 Ma, respectively (Wang et al., 2018b).

6.4. Spatial and temporal distribution of subduction-arc-related magmatism in North Indochina

The spatial and temporal distribution of subduction-arc-related mafic to felsic intrusions in the Truong Son belt can be used to infer the changing of downgoing slab dip. The southward Song Ma suture distribution of the subduction-magmatic arc-related intrusions in the Truong Son belt, from 310 to 247 Ma, reveals a northward younging (Fig. 2). The spatial distribution of these arc-affinity magmatic rocks in the Truong Son belt shows two magmatic belts. The first belt with age 300–260 Ma is distributed between the Thakhet-Po Ko and Rao Nay faults, and the second one with age 260–247 Ma is distributed between the Rao Nay and Song Ma faults. The arc-related magmatic rocks west of the Dien Bien Phu fault also show a similar distribution (Fig. 2). This northward

younging distribution pattern of arc affinity magma in the Truong Son belt can be explained by the rollback of the subducting slab during the subduction-collision of the Sino-Vietnam plate below the Indochina blocks.

The plot $\varepsilon_{\text{Hf}(t)}$ vs U-Pb age of the igneous rocks from Northeast Vietnam, Phan Si Pan-Song Da-Tu Le zone in northwest Vietnam, Ailaoshan-Song Ma zone, and Truong Son belt shows a distinct distribution. Most 310–260 Ma igneous rocks distribute in the southern part of the Truong Son belt and are characterized by positive $\varepsilon_{\text{Hf}(t)}$ values ranging from 0.1 to 13.8 with an average of 5.9. The 260–247 Ma igneous rocks distributed in the northern part of the Truong Son belt, vicinity of the Ailaoshan-Song Ma suture, are characterized by negative $\varepsilon_{\text{Hf}(t)}$ values ranging from -0.3 to -17, average -5.7 (Fig. 9). The distinct transition from positive to negative $\varepsilon_{\text{Hf}(t)}$ values of the magmatism in the Truong Son belt indicates that the magma originated dominantly from the mantle-derived materials in the first stage and more involvement of the older crustal materials in the second one. In the Phan Si Pan-Song Da-Tu Le zone, the Late Permian-Early Triassic magma is characterized by positive $\varepsilon_{\text{Hf}(t)}$ values from 1.9 to 15.9 with an average of 6.9. In the Ailaoshan-Song Ma zone, the 260–247 Ma magmatic rocks exhibit both positive and negative $\varepsilon_{\text{Hf}(t)}$ values, while the 247–230 Ma magma are characterized only by negative $\varepsilon_{\text{Hf}(t)}$ values similar to the felsic magma with the same age in the northeast Vietnam (Fig. 9) and Truong Son belt. The magma younger than 230 Ma in four regions with negative and positive $\varepsilon_{\text{Hf}(t)}$ values indicates the late to post-collisional orogenic magma generated from an inhomogeneous continental crust source.

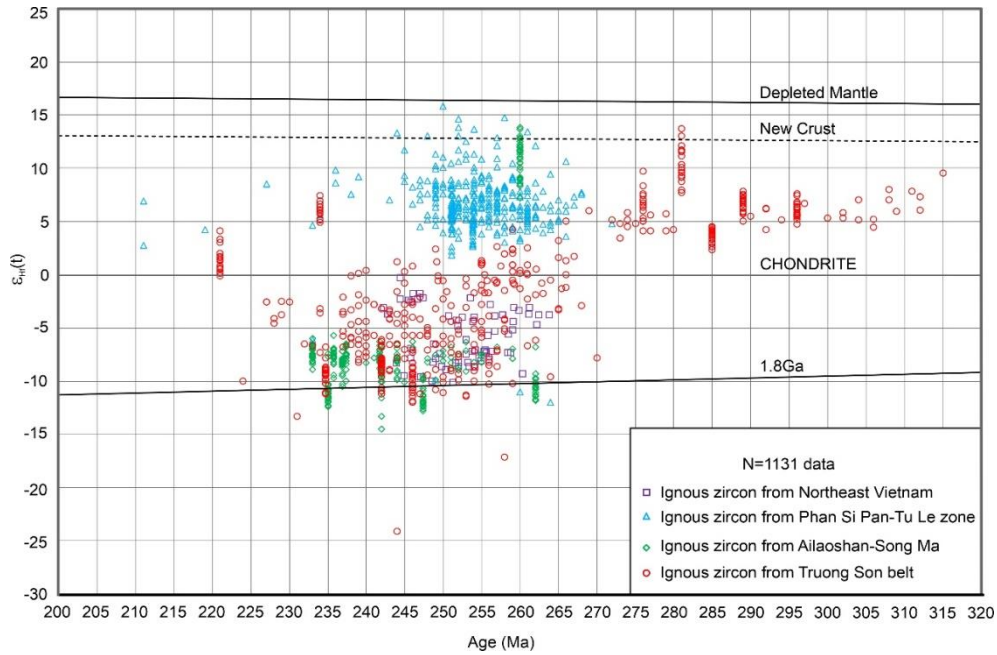


Figure 9. The plot of $\epsilon_{\text{Hf}(t)}$ vs. U-Pb age for zircons with Carboniferous-Triassic ages shows the spatial-temporal trend of the magmatic rocks related to the subduction-collision-orogeny along the Ailaoshan-Song Ma suture zone. Data are from (Hieu et al., 2013; Chen et al., 2014; Hieu et al., 2015; Liu et al., 2015b; Usuki et al., 2015; Wang et al., 2016; Hieu et al., 2017; Minh et al., 2018; Wang et al., 2018a; Hou et al., 2019; Qian et al., 2019; Thanh et al., 2019; Hieu et al., 2020; Dung et al., 2024; Thuy et al., 2024)

6.5. Summary of the tectonic evolution

The process from rifting to Indosinian orogeny is illustrated in Figs. 10, 11, and 12. Figure 10 illustrates the spatial and temporal relationship of the main tectonic blocks, back-arc basin, and suture in the north and west Indochina block from they are rifted off from Gondwana in the Middle Devonian to the ending of the Indosinian orogeny in the Rheatian. Figure 11 is a conceptual reconstruction of the paleotectonic setting for the Sino-Vietnam, Indochina, and Subumasu blocks alongside the related back-arc basin in the Early Permian-Early Triassic. Figure 12 is a schematic section illustrating the tectonic evolution of the tectonic blocks Sino-

Vietnam, Indochina, Sukhothai, and Sibumasu from rifting in Late Devonian to the collision orogeny in the Middle-Late Triassic and summary in the below.

From the Middle Devonian, Sino-Vietnam and Indochina block is rifted from the northern margin of Gondwana. South China and Indochina were separated by the opening of the Paleo-Tethys northern branch, from the Late Devonian to the Middle Carboniferous along the Ailaoshan-Song Ma zone. The second southern branch of Paleo-Tethys separated Sibumasu from Indochina by Sukhothai arc and Jinghong-Nan-Sra Kaeo and Luang Prabang-Loei back-arc basins from 316–255 Ma (Fig. 11 and 12a, b, c).

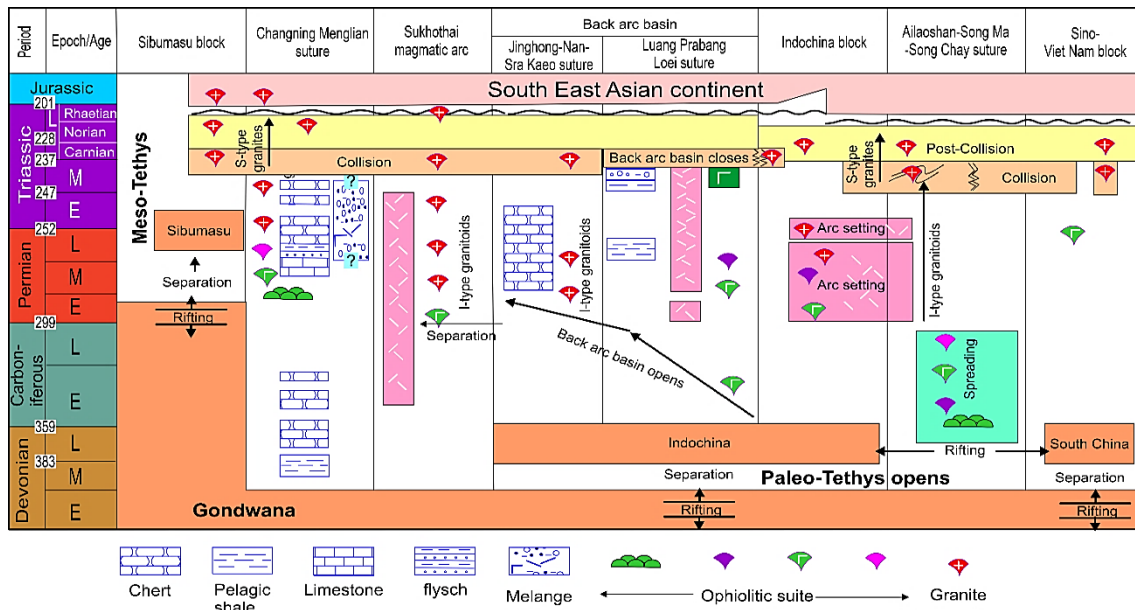


Figure 10. Space-time diagram illustrating the tectonic evolution of the Indochina region (Adapted from Metcalfe (2021))

During the Late Carboniferous-Middle Permian, in response to the continuous northward drift of the Cimmerian continental ribbon, the northward subduction of the Paleo-Tethys southern branch underneath the Indochina blocks induced the Lincang-Sukhothai-East Malaysia arc and Jinghong-Nan-Sra Kao, Luang Prabang-Loei back-arc basins (Fig. 12c-d). This process is also likely responsible for forming basaltic andesite rocks interbedded in the siliciclastic, shale, and limestone of the Dak Lin formation to the west of the Kon Tum massif in Vietnam. At the same time, in the Ailaoshan-Song Ma branch, the Sino-Vietnam slab is subducted with a relatively shallow dip below the Indochina to generate the northern Truong Son arc magmatism between 310–260 Ma (Fig. 12c). It is plausible that the high heat regime rising from the Emeishan plume facilitates the Sino-Vietnam slab rollback from Late Permian ~260 Ma and subsequent the rollback process induces the 260–247 Ma magmatism and Sam Nua back arc (Fig. 12e).

At the beginning of the Middle Triassic, the Ailaoshan-Song Ma ocean was closed, and the Sino-Vietnam block collided with the Indochina block. In contrast, the eastward subduction of the Paleo-Tethys southern branch below the western Indochina block is ongoing (Fig. 12e-f). Such a collision resulted in the HP metamorphism preserved along the Ailaoshan-Song Ma at ~249–230 Ma. The top to the northeast kinematic indicator of the ductile deformation with the synkinematic micas $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 245–240 Ma (Lepvrier et al., 2011; Wang et al., 2022b) supports the southwestward subduction of the Sino-Vietnam block under the Si Mao-Indochina block. This structural data also aligned with the spatial distribution of the arc magmatic development in the northern Truong Son belt. In this period, a dextral shearing affected the Truong Son belt due to an oblique collision between the Indochina and Sino-Vietnam blocks (Lepvrier et al., 1997; Lepvrier et al., 2004). In the southward Tam Ky-Phuoc Son suture zone, lower-middle crustal rocks of the Kon Tum block underwent coevally a top to the northwest extensional exhumation (Faure et al.,

2018). Therefore, mechanically, a roughly north-northeast-south-southwest compressional regime in northeast Vietnam coupled with a

northwest-southeast extensional regime in the Kontum block is likely responsible for such a dextral shearing in the Truong Son belt.

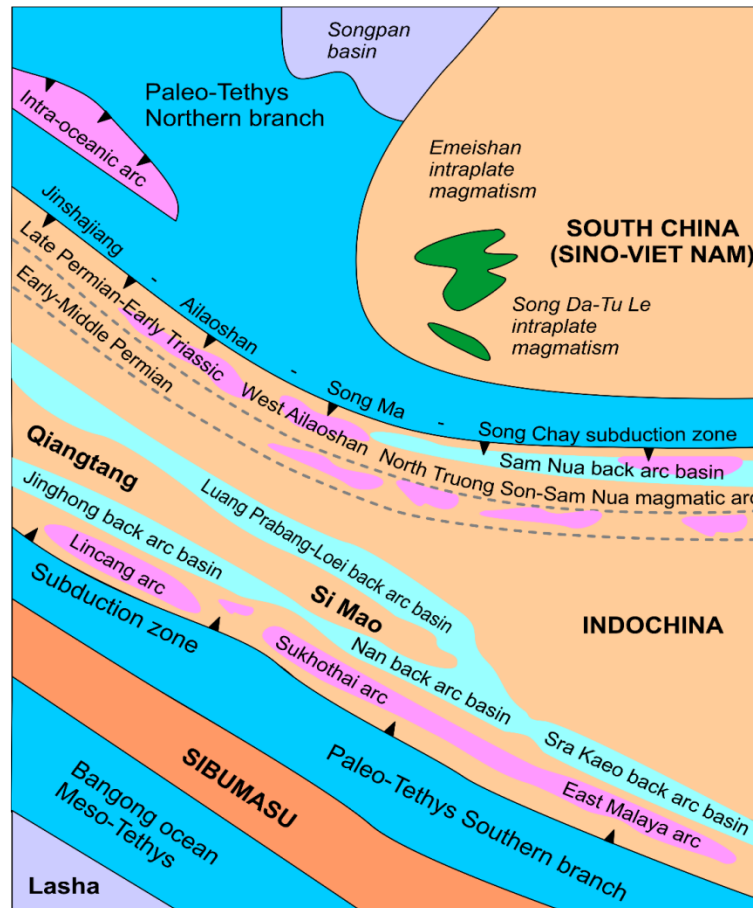


Figure 11. Early Permian-Early Triassic paleo-geodynamic reconstruction for the Sino-Vietnam-Indochina-Sibumasu blocks (Modified after Faure et al., 2014)

In the Ladinian (~240 Ma), the Jinhong-Nan-Sra-Sra Kao back-arc basin closed in response to the initial collision of the Sibumasu-South Qiangtang blocks with the western margin of the Indochina block. Meanwhile, the Indochina block continued to thrust over the Sino-Vietnam block. The downgoing slab breakoff facilitates a rising hot asthenosphere to generate the syn-collision granite and post-collision (Fig. 12f).

In the Ladinian-Carnian, the amalgamation of South China-North Vietnam-Indochina-Sukhothai-Sibumasu formed a united proto-

South-East Asia continent (Fig. 12g). This stage induced two distinct magmas: the syn-collisional magmatism along the western margin of Indochina and the post-collisional magmatism along the Jinshajiang-Ailaoshan-Song Ma and Truong Son orogenic belts.

In the Norian-Rheanian (~230–201 Ma), the crust became too thick, exceeding its strength, and the gravitational collapse of the orogenic belt occurred. This stage induces an elevated regional thermal gradient, resulting in post-collisional igneous activity and exhumation of the metamorphic units along the suture

boundaries and within the main continental fragments of Southeast Asia. Development of the upper Triassic-lowest Jurassic foreland basin and molasse sequence in the north and west Indochina block marked the termination of the Indosinian orogen at ~200 Ma.

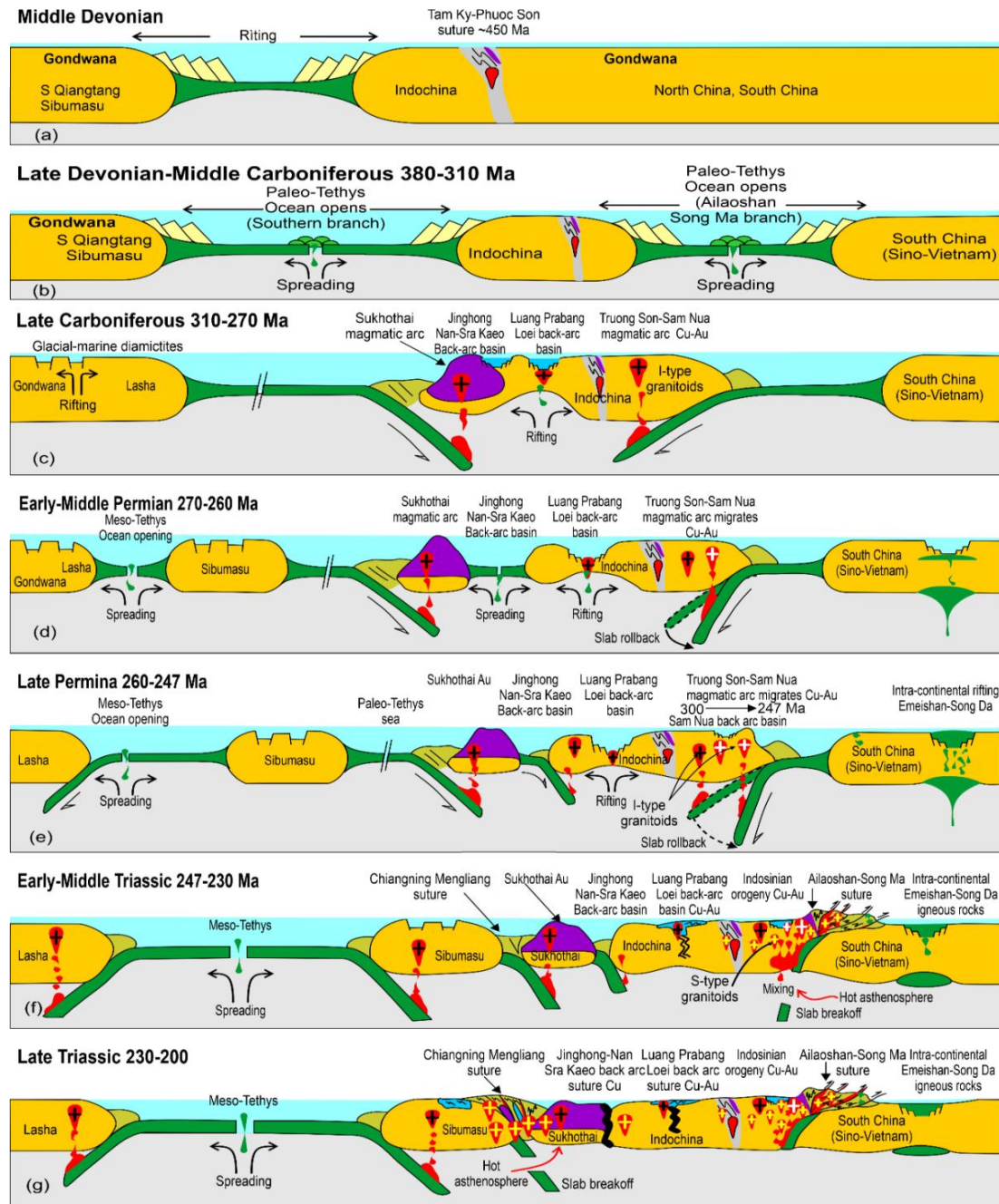


Figure 12. Schematic tectonic cartoons illustrating the evolution of the tectonic blocks Sino-Vietnam, Indochina, Sukhothai, and Sibumasu from rifting in the Late Devonian to the collision orogeny in the Middle-Late Triassic

6.6. Issues need to further research

The basement of the Indochina block is exposed in the Kon Tum massif, located to the south of the Early Paleozoic Tam Ky-Phuoc Son suture zone. Three metamorphic complexes forming the Kon Tum massif also record a Late Permian-Triassic high-grade metamorphism and subsequent exhumation by extensional tectonics indicated by top to the northwest kinematics (Faure et al., 2018). During the Permian-Triassic period, this massif was affected by ultra-high to high-temperature decompression metamorphic conditions (Osanaï et al., 2004; Nakano et al., 2013; Bui et al., 2020). High-temperature magmatism represented by charnokite, enderbite, and gabbro is also emplaced coevally with the high-temperature metamorphism at ~260–250 Ma (Owada et al., 2006; Owada et al., 2007; Owada et al., 2020). Most research links the Triassic metamorphism and magmatism in the Kon Tum massif to the collisional orogeny stage between the Indochina and South China block along the Song Ma suture. However, metamorphism along the Ailaoshan-Song Ma suture zone occurs in a low thermal gradient environment compared to the high thermal gradient environment in the Kon Tum massif. Furthermore, some geochronological and metamorphic data indicated that the Kon Tum massif experienced ultra-high temperature metamorphism with the peak metamorphic condition at 254 Ma (Jiang et al., 2023) earlier than the age of high-pressure eclogite of the Ailaoshan-Song Ma suture dated at 249–230 Ma (Nakano et al., 2008; Nakano et al., 2010; Liu et al., 2013; Zhang et al., 2013; Xuexiang et al., 2018). Therefore, further studies are required to determine whether the collision process along the Ailaoshan-Song Ma suture zone is the driving force causing the Late Permian-Triassic tectono-thermal event in the Kon Tum block.

7. Conclusions

Synthesis of magmatic, metamorphic, sedimentary, stratigraphic, geochemical, isotopic, and geochronological data allows us to highlight the following conclusions for Indochina's Late Devonian to Late Triassic tectonic history and its vicinity.

The rifting and oceanic crust formation along the Ailaoshan-Song Ma is at ~380–313 Ma, along the Changing-Menglian at ~340–260 Ma, along the Jinghong-Nan-Uttaradite-Srakao at ~316–310 Ma.

Southwestward of the Sino-Vietnam block under the Indochina block gave rise to two arc magmatic belts at ~310–260 Ma and 260–247 Ma in the Truong Son belt. The eastward subduction of the Sibumasu block below the Indochina block formed the Sukhothai arc and Jinghong, Nan-Uttaradit, Luang Prabang, Srakao back-arc basin in the Carboniferous-Middle Permian. The magmatic arc develops in ~280–240 Ma. The Sino-Vietnam slab rollback mechanism can interpret the northeastward younging magmatic arc in the Truong Son belt.

The closure of Paleo-Tethys branches resulted in the collision subsequent Indosinian orogeny of the Indochina with Sino-Vietnam blocks at ~250–230 Ma along the Ailaoshan-Song Ma-Song Chay suture, followed by closure of Jinghong, Nan-Uttaradit, Sra Kao back-arc and collision of the Sibumasu block with Indochina-South China continent at ~240–230 Ma along the Channing-Menglian suture.

The late to post-collisional orogenic tectonic event occurred in the north and west Indochina block at ~235–200 Ma and ~230–200 Ma, respectively.

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Appendix

Table 1. Synthesis of geochronological ages for Fig. 2

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
TK61	NE Viet nam	Co Linh	Granodiorite	SIMS	254.8	7.6	Chen et al., 2014
TK164	NE Viet nam	Hong Thai	Quartz-syenite	SIMS	245.5	2.2	Chen et al., 2014
TK216	NE Viet nam	Bach Ha	Biotite Granite	SIMS	227.7	9.6	Chen et al., 2014
TK264	NE Viet nam	Điem Mac	Granodiorite	SIMS	251.8	1.9	Chen et al., 2014
VT16	NE Viet nam	Phia Bioc	Granite	LA-ICP-MS	248.5	1.8	Roger et al., 2012
VT19	NE Viet nam	Phia Bioc	Granite	LA-ICP-MS	245	2	Roger et al., 2012
AN-2437-1	NE Viet nam	Nui Chua	Gabbro	SHRIMP-II	251.2	3.4	Hoa et al., 2008
AN-2419	NE Viet nam	Suoi Cun	Plagioclase-bearing gabbro	SHRIMP-II	262	4	Hoa et al., 2008
AN-2418-2	NE Viet nam		Gabbro-dolerites	SHRIMP-II	266	3.7	Hoa et al., 2008
AN-8003	NE Viet nam	Song Hien	Rhyolite	SHRIMP-II	248	4.5	Hoa et al., 2008
N-1531/1	NE Vietnam	Phia Bioc	Garnet granite	Ar/Ar	250.5	1	Hoa et al., 2008
HQTTD08/1	NE Vietnam	Song Hien	Rhyolite	LA-ICP-MS	254	2.1	Halpin et al., 2014
JH0956	NE Vietnam	Song Hien	Rhyolite	LA-ICP-MS	250.2	2.7	Halpin et al., 2014
JH0957	NE Vietnam	Song Hien	Dacite	LA-ICP-MS	249.6	3.5	Halpin et al., 2014
LS1	NE Vietnam	Song Hien	Rhyolite	LA-ICP-MS	252.9	2.2	Halpin et al., 2014
HQTTD06/1	NE Vietnam	NW Cao Bang	Granodiorite	LA-ICP-MS	251.4	2.2	Halpin et al., 2014
NP175@91.95 m	NE Vietnam	Nui Phao	Granodiorite	LA-ICP-MS	252.2	2.1	Halpin et al., 2014
HQ1554/1	NE Vietnam	Ha Quang	Rhyolite	LA-ICP-MS	382	6	Halpin et al., 2014
JH0948	NE Vietnam	Phia Bioc	Granite	LA-ICP-MS	249.8	2.9	Halpin et al., 2014
JH0950	NE Vietnam	Cao Bang	Peridotite	LA-ICP-MS	274	18	Halpin et al., 2014
	NE Vietnam	Cao Bang	Basalt	Rb/SR TIMS	263	15	Thanh et al., 2014
CH2	NE Vietnam	Chiem Hoa-Na Son	Granite	LA-ICP-MS	252.2	1.4	Tri et al., 2020
NS2	NE Vietnam	Chiem Hoa-Na Son	Quartz syenite	LA-ICP-MS	251.8	1.9	Tri et al., 2020
CH1	NE Vietnam	Chiem Hoa-Na Son	Granite	LA-ICP-MS	250.1	1.5	Tri et al., 2020
NS1	NE Vietnam	Chiem Hoa-Na Son	Quartz syenite	LA-ICP-MS	256.3	1.9	Tri et al., 2020
TDr	NE Vietnam	Tam Dao	Rhyolite	SHRIMP	248	2	Żelaźniewicz et al., 2013
TMd	NE Vietnam	Thac Ba	Diatexite	SHRIMP	264.4	1.3	Żelaźniewicz et al., 2013
TBm	NE Vietnam	Thac Ba	Neosome cut gneiss	SHRIMP	262.9		Żelaźniewicz et al., 2014
S16-65	NE Vietnam	Hat Han	Monzogabbro	SHRIMP-II	247.6	1.1	Svetlitsakaya et al., 2022
S16-59	NE Vietnam	Ban Giem	Quartz monzonite	SHRIMP-II	242	15	Svetlitsakaya et al., 2022
SP18-100	NE Vietnam	Ca Than	Olivine gabbro	SHRIMP-II	248.2	2.3	Svetlitsakaya et al., 2022
SP18-97	NE Vietnam	Nguyen Binh	Monzogabbro	LA-ICP-MS	246.7	1.6	Svetlitsakaya et al., 2022
S16-30/2	NE Vietnam	Bo Ninh	Olivine gabbro	SHRIMP-II	246.9	1	Svetlitsakaya et al., 2022
S16-32	NE Vietnam	Bo Ninh	Plagioclase-bearing lherzolite	SHRIMP-II	248.3	1.2	Svetlitsakaya et al., 2022
SP18-34/1	NE Vietnam	Min Sang	Olivine gabbro	SHRIMP-II	247.7	3.2	Svetlitsakaya et al., 2022
SP18-42	NE Vietnam	Min Sang	Olivine gabbro	SHRIMP-II	246.2	2.4	Svetlitsakaya et al., 2022

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
							2022
SP18-44	NE Vietnam	Min Sang	Granite porphyry	SHRIMP-II	248.4	2.6	Svetlitsakaya et al., 2022
SP18-53	NE Vietnam	Na Hoan	Olivine gabbro	LA-ICP-MS	246.5	1	Svetlitsakaya et al., 2022
SP18-87	NE Vietnam	Lang Den	Granodiorite	LA-ICP-MS	247.6	1.5	Svetlitsakaya et al., 2022
S16-51	NE Vietnam	Suoi Cun	Plagioclase-bearing lherzolite	SHRIMP-II	248.4	2.9	Svetlitsakaya et al., 2022
S16-26	NE Vietnam	Khuoi Khoang	Plagioclase-bearing lherzolite	SHRIMP-II	247.8	4.1	Svetlitsakaya et al., 2022
SP18-71	NE Vietnam	Khuoi Khoang	Plagioclase-bearing lherzolite	SHRIMP-II	254.3	2.9	Svetlitsakaya et al., 2022
S16-21	NE Vietnam	Dong Chang	Plagioclase-bearing lherzolite	SHRIMP-II	424.2	3.2	Svetlitsakaya et al., 2022
SP18-67/5	NE Vietnam	Ha Tri	Plagioclase-bearing lherzolite	LA-ICP-MS	250.1	1.7	Svetlitsakaya et al., 2022
SP18-68	NE Vietnam	Ha Tri area	Rhyolite porphyry	SHRIMP-II	249.3	3.2	Svetlitsakaya et al., 2022
SP18-69	NE Vietnam	Ha Tri area	Rhyolite porphyry	SHRIMP-II	246.3	3.5	Svetlitsakaya et al., 2022
SP18-90/5	NE Vietnam	Na Lung	Quartz monzonite	LA-ICP-MS	250.1	1.9	Svetlitsakaya et al., 2022
NV-06-01	Phan Si Pan NW Vietnam	Kim Boi	Granite	SHRIMP-II	242.4	2.2	Hoa et al., 2008
MH	Phan Si Pan NW Vietnam	Muong Hum	Metagranite	SHRIMP	260	3	Żelaźniewicz et al., 2013
Mhe	Phan Si Pan NW Vietnam	Muong Hum	Enclave in granite	SHRIMP	263.7	1.5	Żelaźniewicz et al., 2013
V0779	Phan Si Pan NW Vietnam	Ye Yen Sun	Granite	LA-ICP-MS	253	2	Hieu et al., 2013
V0783	Phan Si Pan NW Vietnam	Ye Yen Sun	Granite	LA-ICP-MS	251	2	Hieu et al., 2013
V0786	Phan Si Pan NW Vietnam	Nam Xe-Tam Duong	Granite	LA-ICP-MS	253	2	Hieu et al., 2013
V0789	Phan Si Pan NW Vietnam	Nam Xe-Tam Duong	Granite	LA-ICP-MS	251	2	Hieu et al., 2013
LTH12	Phan Si Pan NW Vietnam	Muong Hum	Granite	LA-ICP-MS	259	3.5	Usuki et al., 2015
LTH9	Phan Si Pan NW Vietnam	Muong Hum	Granite	LA-ICP-MS	252.8	7.7	Usuki et al., 2015
BK6	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	253.3	2.6	Usuki et al., 2015
LTH21A	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	257.7	3.7	Usuki et al., 2015
LTH26A	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	248.7	6.9	Usuki et al., 2015
YB24	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	253	2.4	Usuki et al., 2015
YB28	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	265 ± 5		Usuki et al., 2016
YB29	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	253.7	2.5	Usuki et al., 2017
YB31	Phan Si Pan	Phan Si Pan	Granite	LA-ICP-MS	254 ± 5		Usuki et al., 2019

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
	NW Vietnam						
YB27	Phan Si Pan NW Vietnam	Phan Si Pan	Granite	LA-ICP-MS	252.3	5.2	Usuki et al., 2015
PSP37	Phan Si Pan NW Vietnam	Phu Sa Phin	Granite	LA-ICP-MS	256.3	6	Usuki et al., 2015
YB29	Phan Si Pan NW Vietnam	Phan Si Pan	Granosyenite	LA-ICP-MS	253.7	2.5	Usuki et al., 2015
LTH76A	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	259.7	3.1	Usuki et al., 2015
LTH76B	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	259.8	3.1	Usuki et al., 2015
LTH77	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	259.1	3.2	Usuki et al., 2015
LTH81-1	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	261.9	3.2	Usuki et al. 2015
LTH81-3	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	257.9	3.3	Usuki et al., 2015
LTH82	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	258	5	Usuki et al., 2015
YB12	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	254.7	2.6	Usuki et al., 2015
YB19A	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	251.5	5	Usuki et al., 2015
YB21	Phan Si Pan NW Vietnam	Tu Le	Rhyolite	LA-ICP-MS	253.2	2.5	Usuki et al., 2015
V0926	Phan Si Pan NW Vietnam	Muong Hum	Granite	LA-ICP-MS	251.2	3.8	Minh et al., 2018
V0927	Phan Si Pan NW Vietnam	Muong Hum	Granite	LA-ICP-MS	251.1	3.5	Minh et al., 2018
V0928	Phan Si Pan NW Vietnam	Muong Hum	Granite	LA-ICP-MS	253.9	1.5	Minh et al., 2018
TT2	Phan Si Pan NW Vietnam	Tram Tau, Yen Bai	Rhyolite	LA-ICP-MS	258.8	2.2	Tri et al., 2020
TT1	Phan Si Pan NW Vietnam	Tram Tau, Yen Bai	Rhyolite	LA-ICP-MS	258.5	3.2	Tri et al., 2020
V0908	Song Ma	Phia Bioc	Granite	LA-ICP-MS	244	5	Hieu et al., 2017
V0905	Song Ma	Nam Rom	Granodiorite	LA-ICP-MS	231	4	Hieu et al., 2017
V1106	Song Ma		Granite	LA-ICP-MS	239	6	Hieu et al., 2017
V0838-1	Song Ma	Nam He	Granodiorite	LA-ICP-MS	289	5	Hieu et al., 2017
V0838-2	Song Ma	Nam He	Granodiorite	LA-ICP-MS	296	3	Hieu et al., 2017
V0741	Song Ma	Song Ma	Granite	LA-ICP-MS	260	5	Hieu et al., 2017
V0856	Song Ma	Song Ma	Granite	LA-ICP-MS	263	5	Hieu et al., 2017
V1006	Song Ma	Song Ma	Granite	LA-ICP-MS	239	6	Hieu et al., 2017
V0821	Song Ma	Song Ma	Tonalite	LA-ICP-MS	256	7	Hieu et al., 2017
V0903	Song Ma	Nam Rom	Granite	LA-ICP-MS	233	4	Hieu et al., 2017
V0738	Song Ma	Chieng Khuong	Quartz-diorite	LA-ICP-MS	262	4	Hieu et al., 2017
V1703	Song Ma	Muong Luan	Granitoid	LA-ICP-MS	236.9	4.5	Hieu et al., 2020
V1705	Song Ma	Muong Luan	Granitoid	LA-ICP-MS	241.7	4.7	Hieu et al., 2020
V1706	Song Ma	Muong Luan	Granitoid	LA-ICP-MS	237.4	8.3	Hieu et al., 2020
V1708	Song Ma	Muong Luan	Granitoid	LA-ICP-MS	235.8	5.1	Hieu et al., 2020
HH-43A	Ailaoshan	Xin'anzhai granite	Monzogranite	LA-ICP-MS	251.9	1.4	Liu et al., 2015
HH-45A	Ailaoshan	Xin'anzhai	Monzogranite	LA-ICP-MS	251.2	3.1	Liu et al., 2015

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
		granite					
ML-34A	Ailaoshan	Tongtiange	Leucogranite	LA-ICP-MS	247.3	3.1	Liu et al., 2015
ML-34G	Ailaoshan	Tongtiange	Leucogranite	LA-ICP-MS	247.7	3	Liu et al., 2015
MLT09	Song Ma	Muong Lat	Granodiorite	LA-ICP-MS	247.4	2.8	Thanh et al., 2019
MLT08	Song Ma	Muong Lat	Monzogranite	LA-ICP-MS	251	3	Thanh et al., 2019
MLT34	Song Ma	Muong Lat	Monzogranite	LA-ICP-MS	242	0.6	Thanh et al., 2019
MLT42	Song Ma	Muong Lat	Monzogranite	LA-ICP-MS	235	3.1	Thanh et al., 2019
VT225	Song Ma	Chieng Khuong	Granite	LA-ICP-MS	226	6	Roger et al., 2014
VT226	Song Ma	Chieng Khuong	Granite	LA-ICP-MS	232	2	Roger et al., 2014
V0829	Song Ma	Chieng Khuong	Quartz diorite	LA-ICP-MS	271	3	Liu et al., 2012
YXQ01	Ailaoshan	Yaxianqiao	Basalt	SHRIMP	266.2	2.2	Jian et al., 2009
SG04	Ailaoshan		Diabase	SHRIMP	382.9	3.9	Jian et al., 20109
SG02	Ailaoshan		Plagiogranite	SHRIMP	375.9	1.7	Jian et al., 2009
20SM-97	Ailaoshan	Wusu basaltic sequence	Basalt	SHRIMP-II	287	5	Fan et al., 2010
20SM-47	Ailaoshan	Yaxuanqiao volcanic sequence	Basalt	SHRIMP-II	265	7	Fan et al., 2010
YN-71-1	Jinping	Ma'andi	Quartz monzonite	LA-ICP-MS	254	1.3	Liu et al., 2022
YN-75-2	Jinping	Ma'andi	Granite	LA-ICP-MS	254	1	Liu et al., 2022
(K10-25	Jinping	Pinghe	Granite	LA-ICP-MS	257.2	1.6	Lai et al., 2014
K10-29	Jinping	Pinghe	Granite	LA-ICP-MS	255.1	2.2	Lai et al., 2014
VN5-00	Song Ma	Ophiolite complex	Metagabbro	Sm-Nd isochrone	313	32	Vuong et al., 2013
VN18-00	Song Ma	Chieng Khuong	Granite	U-Pb TIMS	222	4	Vuong et al., 2013
VN19-00	Song Ma	Ophiolite complex	Amphibolite	U-Pb Zr TIMS	241.3	5.3	Vuong et al., 2013
VN21-00	Song Ma	Ophiolite complex	Metagabbro	Sm-Nd isochrone	387	56	Vuong et al., 2013
VN22-00	Song Ma	Ophiolite complex	Garnet bearing metagabbro	Sm-Nd isochrone	338	24	Vuong et al., 2013
VN32-00	Song Ma	Ophiolite complex	Gabbro	Sm-Nd isochrone	322	45	Vuong et al., 2013
VN34-00	Song Ma	Ophiolite complex	Amphibolite	Sm-Nd isochrone	315	92	Vuong et al., 2013
VN34-00	Song Ma	Ophiolite complex	Amphibolite	Titanite U-Pb TIMS	265	4	Vuong et al., 2013
SME-04A	Song Ma		Pyroxenite and Rodingite	LA-ICP-MS	340	29	Zhang et al., 2014
IG-33Q	Song Ma		Pl-Amphibole Schist	SIMS	315	3.8	Zhang et al., 2014
15NL-57A	Song Ma		Plagioclase amphibolite	SIMS	356.1	5	Zhang et al., 2020
15NL-57C	Song Ma	Sam Nua	Plagioclase amphibolite	LA-ICP-MS	367.4	3.8	Zhang et al., 2020
15NL-57X	Song Ma	Sam Nua	Granite	LA-ICP-MS	259.5	1.7	Zhang et al., 2020
15NL-55A	Song Ma	Sam Nua	Diabase	LA-ICP-MS	270.1	2.9	Zhang et al., 2020
15NL-59A	Song Ma	Sam Nua	Gabbro	LA-ICP-MS	271.2	2.3	Zhang et al., 2020
15NL-53B1	Song Ma	Sam Nua	Plagiogranites	LA-ICP-MS	261.3	2.1	Zhang et al., 2020

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
15NL-53B4	Song Ma	Sam Nua	Plagiogranites	LA-ICP-MS	258.3	2.7	Zhang et al., 2020
VN12-2	Song Ma		Chieng Khuong Granite	Bi Ar/Ar	245.5	4	Lepvrier et al., 1997
VN10	Song Ma		Chieng Khuong Granite	Bi Ar/Ar	246	4	Lepvrier et al., 1997
VN9	Song Ma		Amphibolite	Amphibole Ar/Ar	266	4	Lepvrier et al., 1997
VN16	Song Ma		Micaschist	Bi Ar/Ar	240	2	Lepvrier et al., 1997
VN8	Song Ma		Micaschist	Mus Ar/Ar	241	4	Lepvrier et al., 1997
VN5	Song Ma		Micaschist	Mus Ar/Ar	237	4	Lepvrier et al., 1997
VN4	Song Ma		Micaschist	Mus Ar/Ar	253	1	Lepvrier et al., 1997
AL2	Truong Son belt	Huong Binh, West Hue	Granite	LA-ICP-MS	255	1.5	Dung et al., 2023
VT228	Truong Son belt	Muong Lay	Granite	LA-ICP-MS	277	2	Roger et al., 2014
DH14	Truong Son belt	Dong Hoi	Granite	LA-ICP-MS	253.3	2.3	Tri et al., 2020
15NL-14B	Truong Son belt	Phonsavan	Granodiorite	LA-ICP-MS	281	1	Qian et al., 2019
15NL-28C	Truong Son belt	Phonsavan	Hornblende granite	LA-ICP-MS	276	1	Qian et al., 2019
15NL-27A	Truong Son belt	Phonsavan	Hornblende granite	LA-ICP-MS	234	1	Qian et al., 2019
15NL-45A	Truong Son belt	Sam Nua	Granodiorite	LA-ICP-MS	221	1	Qian et al., 2019
15NL-23A	Truong Son belt	Phonsavan	Biotite granite	LA-ICP-MS	274	1	Qian et al., 2019
15NL-31A	Truong Son belt	North Laos	Biotite granite	LA-ICP-MS	273	1	Qian et al., 2019
15NL-68A	Truong Son belt	Viengtong	Biotite granite	LA-ICP-MS	272	1	Qian et al., 2019
15NL-69A	Truong Son belt	Viengtong	Biotite granite	LA-ICP-MS	271	1	Qian et al. 2019
15NL-43A	Truong Son belt	Sam Nua	Biotite granite	LA-ICP-MS	260	1	Qian et al. 2019
15NL-60A	Truong Son belt	Sam Nua	Biotite granite	LA-ICP-MS	258	1	Qian et al., 2019
15NL-61A	Truong Son belt	Sam Nua	Biotite granite	LA-ICP-MS	260	1	Qian et al., 2019
15NL-64A	Truong Son belt	Sam Nua	Rhyolite	LA-ICP-MS	261	1	Qian et al., 2019
AL17	Truong Son belt	Huong Binh, West Hue	Biotite granite	LA-ICP-MS	259.3	1.9	Dung et al., 2024
AL14	Truong Son belt	Dak Krong	Granodiorite	LA-ICP-MS	243.2	2.1	Dung et al., 2025
TS26	Truong Son belt	Ben Giang- Que Son	Gabbrodiorite	LA-ICP-MS	278	3.5	Thuy et al., 2023
TS32	Truong Son belt	Ben Giang- Que Son	Gabbrodiorite	LA-ICP-MS	285	3.1	Thuy et al., 2024
LC-1	Truong Son	Lat Boua	Monzogranite	LA-ICP-MS	245.1	2.9	Wang et al., 2016

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
	belt						
LC-8	Truong Son belt	Lat Boua	Monzogranite	LA-ICP-MS	245.9	2.8	Wang et al., 2016
LC-12	Truong Son belt	Kham	Monzogranite	LA-ICP-MS	253.3	1.8	Wang et al., 2016
LC-16	Truong Son belt	Kham	Monzogranite	LA-ICP-MS	234.3	1.5	Wang et al., 2016
LC-17	Truong Son belt	Kham	Monzogranite	LA-ICP-MS	251.2	2.1	Wang et al., 2016
LH-1	Truong Son belt	Phon Thong	Granodiorite	LA-ICP-MS	249	1.9	Wang et al., 2016
LH-4	Truong Son belt	Phon Thong	Granodiorite	LA-ICP-MS	244.5	2	Wang et al. 2016
LH-5	Truong Son belt	Phon Thong	Granodiorite	LA-ICP-MS	249.9	1.8	Wang et al., 2016
LH-11	Truong Son belt	Luu	Tonalite	LA-ICP-MS	238.6	3.2	Wang et al., 2016
LH-13	Truong Son belt	Luu	Tonalite	LA-ICP-MS	236.3	3.2	Wang et al. 2016
LH-16	Truong Son belt	Luu	Tonalite	LA-ICP-MS	234	3.5	Wang et al. 2016
LT-1	Truong Son belt	Na The	Granodiorite	LA-ICP-MS	254.4	2.5	Wang et al., 2016
LT-3	Truong Son belt	Na The	Granodiorite	LA-ICP-MS	256.4	3.1	Wang et al., 2016
LT-4	Truong Son belt	Na The	granodiorite	LA-ICP-MS	240.1	1.6	Wang et al., 2016
LT-6	Truong Son belt	Na The	granodiorite	LA-ICP-MS	244.8	3.9	Wang et al. 2016
Zk8206-B02	Truong Son belt	Pha Lek	Felsic Pluton	LA-ICP-MS	285.2	4.9	Hou et al., 2019a
NBT-B04	Truong Son belt	Nam Pathene	Monzogranite	LA-ICP-MS	259	1	Hou et al., 2019
NBT-B01	Truong Son belt	Nam Pathene	Porphyritic granite	LA-ICP-MS	262	1	Hou et al., 2019
D0505B2	Truong Son belt	Nanou	Diorite porphyry	LA-ICP-MS	276	2	Hou et al., 2019
D0611B1	Truong Son belt	Sam Nua	Rhyolite	LA-ICP-MS	251	2	Hou et al., 2019
Nalou Ore district	Truong Son belt	Sepon	Granodiorite porphyry	LA-ICP-MS	302.1	2.9	Wang et al., 2018
V1102	Truong Son belt	Hai Van	Granite	LA-ICP-MS	234.7	3.7	Hieu et al., 2015
V1102-3	Truong Son belt	Hai Van	Granite	LA-ICP-MS	224	4.6	Hieu et al., 2015
V1114	Truong Son belt	Hai Van	Granite	LA-ICP-MS	242	2.4	Hieu et al., 2015
V1124	Truong Son belt	Hai Van	Granite	LA-ICP-MS	235	14	Hieu et al., 2015
V1125	Truong Son belt	Hai Van	Granite	LA-ICP-MS	242.1	4.8	Hieu et al., 2015
V1127	Truong Son belt	Hai Van	Granite	LA-ICP-MS	241.4	2	Hieu et al., 2015
H227/92	Truong Son	Tien Phuoc	Granite	SHRIMP	260	4	Hoa et al., 2008

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
	belt						
HSD01@63.8 m	Truong Son belt	Ban Houayxai	Feldspar-phyric andesite	LA-ICP-MS	286	4	Manaka et al., 2014
HSD04@51.9 m	Truong Son belt	Ban Houayxai	Crystal-rich volcanic breccia	LA-ICP-MS	283	4	Manaka et al., 2015
ACH066	Truong Son belt	Long Chieng Track	Quartz monzonite	LA-ICP-MS	292	3	Manaka, 2008
LSD09	Truong Son belt	LCT	Feldspar-phyric dacitic porphyry	LA-ICP-MS	290.6	3.5	Manaka, 2008
VN12-050	Truong Son belt	Ben Giang- Que Son	Granodiorite porphyry	LA-ICP-MS	252	2	Shi et al., 2015
JH0810	Truong Son belt	Bong Mieu	Diorite	LA-ICP-MS	252	2	Hai et al., 2014
JH0822	Truong Son belt	Bong Mieu	Granite	LA-ICP-MS	246	3	Hai et al., 2015
62,701	Truong Son belt	Nam Pathene	Granodiorite porphyry	Ar/Ar Bio	247	1	Sanematsu et al., 2011
70,114	Truong Son belt	Nape	Tonalite	Ar/Ar Bio	209	2	Sanematsu et al., 2011
70,102	Truong Son belt	Nape	Granodiorite porphyry	Ar/Ar Bio	222	1	Sanematsu et al., 2011
62,903	Truong Son belt	Nape	Granodiorite porphyry	Ar/Ar Bio	235	1	Sanematsu et al., 2011
62,815	Truong Son belt	Phou Thoun	Granitic gneissic	Ar/Ar Mus	251	1	Sanematsu et al., 2011
63,001	Truong Son belt	Poung Kuak	Two micas granite	Ar/Ar Mus	244	1	Sanematsu et al. 2011
62,814	Truong Son belt	Phou Thoun	Granodiorite porphyry	Ar/Ar Bio	253	1	Sanematsu et al. 2011
VN12-056	Truong Son belt	Pho Chau	Monzogranite	LA-ICP-MS	261	3	Shi et al., 2015
19.467N	Truong Son belt	Phu He	Andesite	LA-ICP-MS	291	4	Hotson, 2009
103.256E	Truong Son belt	Phu Kham	Dacite	LA-ICP-MS	290	3	Hotson, 2009
	Truong Son belt	Phu Kham	Dacitic breccia	LA-ICP-MS	290	3	Hotson, 2009
GDD05	Truong Son belt	Phu Kham	Diorite porphyry	LA-ICP-MS	304	2	Kamwong et al., 2014
PH1	Truong Son belt	Phu Kham	Diorite porphyry	LA-ICP-MS	306	1	Kamwong et al., 2014
19.417 N 103.195E	Truong Son belt	Phu Kham	Diorite	LA-ICP-MS	290	3	Hotson, 2009
	Truong Son belt	Phu Kham	Diorite	LA-ICP-MS	287	4	Hotson, 2009
	Truong Son belt	Phu Kham	Diorite	LA-ICP-MS	285	2	Hotson, 2009
	Truong Son belt	Phu Kham	Tonalite	LA-ICP-MS	282	2	Hotson, 2009
	Truong Son belt	Phu Kham	Tonalite	LA-ICP-MS	280	4	Hotson, 2009
	Truong Son belt	Phu Kham	Tonalite	LA-ICP-MS	277	3	Hotson, 2009
KHN0130785	Truong Son	Sepon	Rhyodcite	LA-ICP-MS	283	3	Cromie, 2010

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
	belt		porphyry				
PDN0022740	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	287	2	Cromie, 2010
NLU0610460	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	280	6	Cromie, 2010
TKW0531157	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	282	2	Cromie, 2010
BNG5410861	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	289	2	Cromie, 2010
PCNAK03001	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	290	2	Cromie, 2010
TKW0531307	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	297	4	Cromie, 2010
PCDSW03001	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	284	5	Cromie, 2010
PCTKM03001	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	288	2	Cromie, 2010
PCDSW03010	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	283	6	Cromie, 2010
DIS0250860	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	286	3	Cromie, 2010
DSC5531414	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	290	6	Cromie, 2010
PCTKM03003	Truong Son belt	Sepon	Rhyodcite porphyry	LA-ICP-MS	288	3	Cromie, 2010
BSK5531424	Truong Son belt	Sepon	Granite	LA-ICP-MS	243	3	Cromie, 2010
BSK5531425	Truong Son belt	Sepon	Granite	LA-ICP-MS	247	4	Cromie, 2010
LA00003	Truong Son belt	Pha Lek D2 pluton	Monzogranite	LA-ICP-MS	280	3	Wang et al., 2013
D926	Truong Son belt	Ban Vang	Granite	LA-ICP-MS	261	1	Gao et al., 2016
V0845	Truong Son belt	Dien Bien	Granodiorite	LA-ICP-MS	229	3	Liu et al 2012
V0844	Truong Son belt	Dien Bien	Quartz monzonite	LA-ICP-MS	202	4	Liu et al 2012
VN12-066	Truong Son belt	Dien Bien	Granodiorite	LA-ICP-MS	242	3	Shi et al., 2015
VN12-022	Truong Son belt	Ha Tinh	Monzogranite	LA-ICP-MS	253.4	1.7	Shi et al., 2015
VN12-025	Truong Son belt	Dong Trau	Rhyolite	LA-ICP-MS	252	2	Shi et al., 2015
VN12-050	Truong Son belt	Ben Giang- Que Son	Plagiogranite	LA-ICP-MS	251.8	1.9	Shi et al., 2015
VN12-066	Truong Son belt	Dien Bien	Granodiorite	LA-ICP-MS	242.2	1.3	Shi et al., 2015
V0852-4	Truong Son belt	Muong Lay	Diorite	LA-ICP-MS	276	5	Liu et al., 2012
SVN42	Truong Son belt	Ben Giang- Que Son	Granodiorite	LA-ICP-MS	296	3	Sang, 2011
SVN42.1	Truong Son belt	Ben Giang- Que Son	Quartz diorite	LA-ICP-MS	295	4	Sang, 2011
SVN43.1	Truong Son	Ben Giang-	Quartz diorite	LA-ICP-MS	297	5	Sang, 2011

Sample name	Region	Location/ Complex	Petrology	Method	Age (Ma)	Err	Reference
	belt	Que Son					
SVN48.1	Truong Son belt	Ben Giang- Que Son	Gabbrodiorite	LA-ICP-MS	306	2	Sang, 2011
SVN73	Truong Son belt	Ben Giang- Que Son	Gabbrodiorite	LA-ICP-MS	283	6	Sang, 2011
SVN73.2	Truong Son belt	Ben Giang- Que Son	Biotite granite	LA-ICP-MS	278	3	Sang, 2011
VT288	Truong Son belt	Muong Lay	Granodiorite	LA-ICP-MS	277	2	Roger et al., 2014
VT226	Truong Son belt	Dien Bien	Granite	LA-ICP-MS	230	1	Roger et al., 2014
VT225	Truong Son belt	Dien Bien	Granite	LA-ICP-MS	225	3	Roger et al., 2015
01082303C	Truong Son belt	Hai Van	Granite	Monazite CHEME	239	6	Nakano et al., 2013
01082304C	Truong Son belt	Hai Van	Granite	Monazite CHEME	237	6	Nakano et al., 2013
01082402B	Truong Son belt	Hai Van	Granite	Monazite CHEME	222	6	Nakano et al., 2013
01082403D	Truong Son belt	Hai Van	Granite	Monazite CHEME	231	10	Nakano et al., 2013
05030101B	Truong Son belt	Hai Van	Granite	Monazite CHEME	232	5	Nakano et al., 2013
05030101B	Truong Son belt	Hai Van	Granite	Monazite CHEME	219	7	Nakano et al. 2013
05030207B	Truong Son belt	Hai Van	Granite	Monazite CHEME	224	5	Nakano et al., 2013
05030207B	Truong Son belt	Hai Van	Granite	Monazite CHEME	223	6	Nakano et al., 2013
05030209A	Truong Son belt	Hai Van	Tonalite	Monazite CHEME	229	6	Nakano et al., 2013
Zk4207-B07	Truong Son belt	Pha Lek	Felsic Pluton	LA-ICP-MS	285.7	1.5	Hou et al., 2019a
LC-6	Truong Son belt	Lat Boua	Monzogranite	LA-ICP-MS	254.9	1.6	Wang et al., 2017
VN9	Truong Son belt	Bu Khang	Orthogneiss	SHRIMP-II	244	5	Cater et al., 2014