Evolution of supracrustal rocks of the Indochina Block: Evidence from new detrital zircon U–Pb ages of the Kontum Massif, Central Vietnam

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The Kontum Massif and the Truong Son Belt, central Vietnam are the magmatic–metamorphic massifs (belts) of the Indochina Block. These two massifs (belts) underwent two independent orogenic events during Ordovician–Silurian and Permian–Triassic ages. However, due to the strong overprint of these two orogenic events, the evidence of any preexisting (e.g., Precambrian) tectono–thermal events have become extremely poor. Hence, the Precambrian age components of the Indochina Block have not been fully revealed, and their implication is not well-understood. It is well known that such ‘lost memories’ of the older continental rocks or source crustal materials are sometimes preserved in the sedimentary basins. Keeping that goal in mind, we have investigated the LA–ICP–MS detrital zircon U–Pb dating for three sedimentary and metasedimentary rocks in the Kontum Massif and southern part of the Truong Son Belt, Indochina Block, central Vietnam to unravel the Precambrian episodes of the Indochina Block, if any. Two Triassic (meta)sedimentary rocks reveal two significant age clusters of latest Carboniferous to Triassic (~ 300–230 Ma) and Early Paleozoic (~ 480–410 Ma), with the conspicuous lack of the 400–320 Ma zircon grains. Abundant Permian detrital zircon grains in Triassic metaquartzite from the Kontum Massif document that the subduction–related magmatism before the continental collision played an important role in the growth of the Kontum Massif. In contrast to these two (meta)sedimentary rocks, the detrital zircon spectra of metaquartzite from the Kontum Massif show the most significant age peak of ~ 1780 Ma and abundant Archean zircon grains (16%). Furthermore, the oldest detrital zircon shows the Paleoproterozoic age (~ 2070 Ma) and the youngest detrital zircon yields the 207Pb/206Pb spot age of 1359 ± 85 Ma. Hence, the approximate depositional timing of the protolith of metaquartzite was in Mesoproterozoic time.

The newly obtained detrital zircon data indicate a significant contribution of the Paleoproterozoic crustal materials during the deposition of the quartzite in the Kontum Massif. The Kontum Massif had developed as a different unit in the Precambrian period from the Truong Son Belt as well as the southwestern Yangtze Block due to their different Precambrian provenance. This study reveals a new clue that the Kontum Massif was one of the Precambrian blocks in the Southeast Asian massifs.

Keywords: Kontum Massif, Indochina Block, LA–ICP–MS zircon U–Pb age, Supracrustal rock, Southeast Asia

INTRODUCTION

The Asian continent was formed as a result of the collision of several continental blocks such as the North China, South China, and Indochina blocks (e.g., Metcalfe, 1996; Carter et al., 2001; Metcalfe, 2006, 2013; Wang et al., 2018). Based on the good amount of petrological and geochronological database, the Precambrian evolution history of the North China Block is relatively well constrained (e.g., Zhao and Cawood, 2012; Zhao and Zhai, 2013; Cho et al., 2017; Wang et al., 2020a,
Hence, the crustal zircon (e.g., Usuki et al., 2013; Hung et al., 2019).

e al., 2015, 2016; Minh et al., 2020a), and river-sand zircon (e.g., Usuki et al., 2013; Hung et al., 2019). Hence, the crustal-growth history of the Indochina Block can be traced back to the Precambrian. In addition, most recent studies revealed the meaningful Precambrian magmatic ages from the Indochina Block of ~ 1450 Ma (the Kontum Massif, central part of the Indochina Block; Nakano et al., 2021) and 867 ± 19 Ma (the Simao terrane, northwestern part of the Indochina Block; Kang et al., 2019) from the zircon U-Pb dating of the (meta)-igneous rocks. These new findings confirmed the Precambrian igneous activity of the Indochina Block. Despite the above reports, detailed timings of the Precambrian events or the character of the Precambrian source materials are still loosely constrained due to the limited evidence from the exposed rock units. This makes it difficult to construct the paleo-geographic position of the Indochina Block as a part of the supercontinental cycles such as Rodinia and/or Gondwana. Regarding this, unraveling the Precambrian evolutionary histories of the Indochina Block as a part of the Precambrian continental blocks of Asia is important to reconstruct the break-up and amalgamation process of the supercontinent. In addition, the Indochina Block collided with the South China Block on its north along the Song Ma suture (e.g., Cai and Zhang, 2009; Nakano et al., 2010, 2013; Yonemura et al., 2013; Faure et al., 2014; Hieu et al., 2015, 2017; Thanh et al., 2019; Hieu et al., 2020a) (Fig. 1a). Although the Precambrian evolutionary history of the South China Block side has been reported (Hieu et al., 2012; Zhao et al., 2019a, 2019b; Hieu et al., 2020b; Minh et al., 2020b), data from the Indochina Block side is extremely poor as mentioned above. To provide important constraints on the Precambrian crustal formation of the Southeast Asian continent, precise understandings of the Precambrian crustal growth history of the Indochina Block side are necessary.

Detrital zircon grains from sediments rocks preserve the age information of provenance owing to their durability against chemical and physical effects during the transportation, deposition, and subsequent burial pro-

cesses. Besides, low to medium-grade metamorphism does not reset the initial age information due to the high closure temperature of the U-Pb system in zircon (higher than 900 °C; Cherniak and Watson, 2000). Hence, detrital zircon grains put important constraints on the Precambrian crustal growth history. Detrital zircon grains from the sedimentary rocks possibly hold key age data on the existence of the Precambrian source rocks as well as the ‘lost memory’ of the Precambrian orogenic events of the Indochina Block. In this respect, supracrustal rocks have the potential to detect their origin and tectonic affinity of the basement Massif.

In this study, we integrate new results on the petrography and U-Pb geochronology of detrital zircon from the three (meta)-sedimentary rocks in the Kontum Massif and southern part of the Truong Son Belt (also called the Northern Kontum Massif), to provide a comprehensive picture of the Precambrian continental crust evolution of the Indochina Block. The new data provides evidence to constrain the Precambrian tectonic evolution of the Indochina Block in the Southeast Asian continent.

**GEOLOGICAL OUTLINE**

Southeast Asia had been formed by the amalgamation of some continental blocks, including the Indochina, Sibumasu, and South China blocks (Fig. 1a). The Indochina Block is situated at the eastern part of the Indochina Peninsula and is aligned with the South China Block to the north and with the Sibumasu Block to the west (Fig. 1a). The South China Block is further divided into Yangtze Block to the west and Cathaysia Block to the east. These two blocks were amalgamated at ~ 0.87–0.80 Ga, which formed the present South China Block (Charvet, 2013). The Song Ma zone in northwest Vietnam has been considered as part of the suture zone between the Indochina and South China blocks after the closure of the Paleo-Tethys Ocean (Hieu et al. 2017; Thanh et al., 2019; Fig. 1a). Within the territory of Vietnam, the Indochina Block encompasses main tectonic units, i.e., Truong Son Belt, Kontum Massif, and Dalat Zone (Fig. 1a). The Kontum Massif and the Truong Son Belt are situated in central Vietnam and are separated by the Tam Ky-Phuoc Son suture zone (Shi et al., 2015; Faure et al., 2018; Nguyen et al., 2019; Fig. 1a). The Dalat Zone in southcentral Vietnam is defined as a Cretaceous magmatic complex (e.g., Thuy et al., 2004a, 2004b; Shellnutt et al., 2013).

The present study provides new U-Pb geochronological data from detrital zircon in the Kontum Massif and southern part of the Truong Son Belt. They were first recognized as the Precambrian basement of the Indochina Block (e.g., Hutchison, 1989; Nam et al., 2001; Nagy et
al., 2001; Lan et al., 2003; Roger et al., 2007) but more recently, Ordovician–Silurian and Permian–Triassic tectonic events have widely been documented from these two units (Nam et al., 2001; Roger et al., 2007; Nakano et al., 2007, 2009, 2010, 2013; Faure et al., 2018; Nguyen et al., 2019; Minh et al., 2020a; Nakano et al., 2021). The Kontum Massif is characterized by the presence of high–grade metamorphic rocks up to the eclogite and/or granulite facies and numerous intrusive rocks (Fig. 1b). Traditionally, the Kontum Massif is divided into three Complexes based on the metamorphic conditions, namely the Kannak Complex (granulite facies), the Ngoc Linh Complex (amphibolite to granulite facies accompanied with eclogite facies predating retrograde granulite facies overprint), and the Kham Duc Complex (greenschist to amphibolite facies) (Nakano et al., 2007, 2013; Fig. 1b). The Kontum Massif has long been documented as the Precambrian core of the Indochina Block (Hutchison, 1989). Nakano et al. (2021) reported the ∼1450 Ma magmatism from the Triassic metagneous rocks of the Kontum Massif as a zircon U–Pb dating. However, Precambrian magmatic rocks were not recognized in the southern part of the Truong Son Belt (Fig. 1b). Based on the recent progress of the geochronological studies, two–stages of the Phanerozoic magmatic–metamorphic activities are considered to have generated rocks widely distributed in the Kontum Massif and the Truong Son Belt. One is at Ordovician to Silurian time (e.g., Nagy et al., 2001; Nakano et al., 2007; Roger et al., 2007; Shi et al., 2015; Hieu et al. 2016; Minh et al. 2020a), and the other is at Permian to Triassic period (e.g., Nakano et al., 2013; Faure et al., 2018; Bui et al., 2020). These main episodes can be recognized independently from the three metamorphic Complexes (Nakano et al., 2013; Bui et al., 2020). Among them, Permian to Triassic episode is the most significant event and is generally accepted as a result of the continental collision between the Indochina Block and the South China Block (e.g., Osanai et al., 2004, 2008; Nakano et al., 2009, 2013; Hieu et al., 2015; Thanh et al., 2019; Hieu et al., 2020a). Nakano et al. (2004) and Osanai et al. (2004, 2008) revealed the high–to ultrahigh–pressure metamorphism before the retrograde ultrahigh–temperature granulite facies metamorphism, which displays clockwise P–T path. They concluded this P–T evolution as triggered by the continental collision event. In contrast, the intracontinental tectonic models also have been proposed from several studies (e.g., Carter et al., 2001; Metcalfe, 2013) to explain the Permian–Triassic metamorphic–magmatic events. The Ordovician to Silurian event is thought to have been formed by the tectonism under the subduction–related arc setting due to its low P/T metamorphism (Nakano et al., 2013; Gardner et al., 2017). However, continental collision models are also proposed to explain the Ordovician to
Silurian magmatic–metamorphic–tectonic events as a result of the amalgamation between Viet-Lao Block (Truong Son Belt) and Viet-Cambodia Block (Kontum Massif) along the Tam Ky–Phuoc Son suture zone in response to the closure of the oceanic crust (Faure et al., 2018; Jiang et al., 2020) (Fig. 1a). The Tam Ky–Phuoc Son suture zone is located in the north of the Kontum Massif (Figs. 1a and 1b) and is considered as the major fault zone accompanying the ophiolitic ultramafic–mafic sections (e.g., Izokh et al., 2006; Tran et al., 2014; Nguyen et al., 2019). North of the Tam Ky–Phuoc Son suture zone will be referred to as the Truong Son Belt (Fig. 1a). Zircon U–Pb ages of 519–502 Ma Dieng Bong plagiogranite, 454–445 Ma Chu Lai granite, and 427–423 Ma Dai Loc granite also support the presence of an Early Paleozoic suture zone between the Kontum Massif and the Truong Son Belt (Hieu et al., 2016; Nguyen et al., 2019; Minh et al., 2020a; Fig. 1b). However, the structural features and geochronological characters of the Tam Ky–Phuoc Son suture zone are not well constrained. Based on the Early Paleozoic continental collision model, the Indochina Block was formed as a result of the collision between Viet-Lao Block (Truong Son Belt) and Viet-Cambodia Block (Kontum Massif) along the Tam Ky–Phuoc Son suture zone (Faure et al., 2018).

The southern part of the Truong Son Belt is characterized by weakly– to non-metamorphosed Paleozoic to Mesozoic sedimentary rocks. In contrast to the Kontum Massif, the existence of the Precambrian crustal growth has not been discovered in the southern part of the Truong Son Belt. Weakly-metamorphosed rocks in the southern part of the Truong Son Belt are schistose in nature. Numerous plutonic rock bodies are intruded in the southern part of the Truong Son Belt, similar to the Kontum Massif (Fig. 1b). The dextral strike-slip faults are developed in the Truong Son Belt (Lepvrier et al., 1997, 2004). The detrital zircon age of the sedimentary rocks from Cambrian to Devonian formations in the Truong Son Belt have dominant age peaks of ~ 445 and ~ 964 Ma with the broad multiple minor peaks from latest Archean to Cambrian. Age spectra of the Precambrian periods are interpreted as of the Gondwana affinity (Wang et al., 2016).

In the Kontum Massif and the Truong Son Belt, several intrusive bodies are recognized (Fig. 1b). Magmatic timing of those intrusive bodies is divided into two stages, e.g., Early Paleozoic age (e.g., Carter et al., 2001; Nagy et al., 2001; Hieu and Trung, 2015; Hieu et al., 2016; Jiang et al., 2020; Minh et al., 2020a) and Permian–Triassic age (e.g., Sang, 2011; Hieu et al., 2015). Two stages of the magmatic complexes are distributed in both the Kontum Massif and the Truong Son Belt.

FIELD OCCURRENCES AND SAMPLE DESCRIPTION

We collected two metaquartzite (KTM-Qtz1814, KTM-Qtz1818) samples from the Kontum Massif and one sandstone (KTM-Ss1923) sample from the southern part of the Truong Son Belt to obtain the detrital zircon U–Pb ages (Fig. 1b). Sample descriptions are summarized in Table 1.

Metaquartzite sample (KTM-Qtz1814: 14°23′09.5″N, 107°52′25.8″E) was taken from the Kham Duc Complex, Kontum Massif (Fig. 1b). The outcrop of the metaquartzite is smaller than the mappable size in Figure 1b and sporadically found surrounded by the granitoids. The rock displays a pale–white color (Fig. 2a). The main rock–forming minerals of this sample are quartz and mi-

Table 1. Result of the LA-ICP-MS detrital zircon dating of three samples

| Sample name | KTM-Qtz1814 | KTM-Qtz1818 | KTM-Ss1923 |
|-------------|-------------|-------------|------------|
| **Rock type** | Metaquartzite | Metaquartzite | Sandstone |
| **Location** | Kontum Massif | Kham Duc Complex | Southern part of the Truong Son Belt |
| **Complex or Formation** | Nong Son Formation | | |
| **Latitude** | 14°23′09.5″N | 14°26′56.4″N | 15°46′15.1″N |
| **Longitude** | 107°52′25.8″E | 107°50′27.7″E | 107°48′36.6″E |
| **Number of the measured spot** | 58 | 134 | 82 |
| **Number of the concordant data** | 42 | 86 | 68 |
| **Youngest detrital zircon age** | 228.3 ± 11.7 Ma | 1359 ± 85 Ma | 226.0 ± 9.1 Ma |
| **Metamorphic recrystallized age** | none | 413.6 ± 16.0 Ma | none |
| **Peak ages (Ma) and their percentage (%)** | ~ 300–230 Ma (86%) | ~ 1900–1600 Ma (71%) | ~ 270–230 Ma (47%) |
| | ~ 480–450 Ma (7%) | Older than 2350 Ma (23%) | ~ 480–400 Ma (31%) |
| | ~ 1440–1360 Ma (5%) | | ~ 1470–1420 Ma (7%) |
nor muscovite (Fig. 2d). Plagioclase is not observed in this sample. Sillimanite, zircon, rutile, and corundum occur as accessory minerals. Muscovite contains fine-grained quartz, indicating that it was grown during metamorphism (Fig. 2d). Due to the lack of any deformation texture, the quartzite might have suffered contact metamorphism.

Metaquartzite sample (KTM-Qtz1818: 14°26′56.4″N, 107°50′27.7″E) was also collected from the Kham Duc Complex, Kontum Massif (Fig. 1b). In the field, the outcrop of the metaquartzite occurs in a discontinuous manner. Metacarbonate rocks are accompanied by metaquartzite rocks. Granitoids are widely distributed in this region (Fig. 1b). The outcrop of metaquartzite is also not in the mappable size in Figure 1b. The rock displays a transparent reddish-white color and shows a clear foliation in the field (Fig. 2b). The main rock-forming minerals are quartz and muscovite (Fig. 2e). Plagioclase and K-feldspar are not found in this sample. Zircon, rutile, and tourmaline occur as accessory phases. The grain-boundary migration is evident in quartz grains (Fig. 2e), which implies that the quartzite was metamorphosed under high-temperature conditions. However, it is difficult to estimate the precise metamorphic conditions due to its nearly mono-mineralic character and lack of any other index minerals of the metamorphic grade.

Sandstone sample (KTM-Ss1923: 15°46′15.1″N, 107°48′36.6″E) was taken from the Nong Son Formation, the southern part of the Truong Son Belt (Fig. 1b). The Nong Son Formation is a Triassic sedimentary basin developed in the Truong Son Belt (Tri and Khuc, 2011). The Nong Son Formation unconformably overlies the Early Paleozoic A Vuong Formation to the north and is unconformably overlain by Jurassic sedimentary rocks (Fig. 1b). The southern limit of this Formation is marked by a fault contact with the southerly-bound metamorphic and magmatic rocks of the Truong Son Belt (Fig. 1b). In the field, thin layers of the mudstone are interbedded within the sandstone layers parallel to the bedding plane. The sample displays a pale reddish color (Fig. 2c). The main rock-forming minerals of sample KTM-Ss1923 are quartz and minor muscovite (Fig. 2f). Garnet and zircon appear as accessory minerals. This sample can be classified as a quartzose wacke.

**SAMPLE PREPARATION AND ANALYTICAL PROCEDURES**

Zircon separation technique and sample preparation procedure are the same as those detailed in Kawaguchi et al. (2020). Utmost care was taken to avoid any contamination during the sample preparation process. In this study,
all the heavy and non-magnetic minerals are mounted for three samples to avoid the human bias, of which possibly contains the various featured zircon grains from the different provenance. Zircon FC1 (207Pb/206Pb age of 1099.0 ± 0.6 Ma; Paces and Miller, 1993) was used for correction of the U–Pb ratio, and glass standard NIST SRM 610 was used for correction of Th/U ratio. Cathodoluminescence (CL) images of zircon grains were taken using a scanning electron microprobe (SEM: JEOL JSM 7500F) installed at the Department of Earth and Planetary Systems Science, Hiroshima University, Japan. Zircon U–Pb isotope analysis was performed using a 213 nm Nd-YAG Laser (New Wave Research UP-213) attached with an inductively coupled plasma ionization mass spectrometer (Thermo Fisher X-Series-II) (LA-ICP-MS) installed at the same university. The detailed analytical methodology used was described by Katsube et al. (2012, their Table 1). The laser spot diameter of 25 µm and the repetition of 4 Hz was chosen during analysis. During the analysis, zircon YO1 (TIMS 206Pb/238U age of 279.3 Ma, leached zircon; Herzig et al., 1997) was measured as an unknown sample to confirm the data quality. Raw data were processed using the data reduction program PepiAGE (Dunkl et al., 2008), and final statistical plotting used Isoplot/Ex (Version 3.71; Ludwig, 2003). During this analytical session, the weighted average 206Pb/238U age from zircon standard YO1 was 277.9 ± 3.5 Ma (n = 10, MSWD = 0.22), which is consistent with the recommended value. In this study, 206Pb/238U ages are used for the zircon younger than 1000 Ma, while 207Pb/206Pb ages are used for the zircon older than 1000 Ma. In general, older zircon data (e.g., Precambrian) are plotted out of the Concordia curve even for a small discordance value, while young zircon data (e.g., Phanerozoic) are plotted on the Concordia curve even if the discordance value is large. Noticing this, concordant data was selected with the discordance (defined as the age difference between 206Pb/238U age and 207Pb/235U(U) age) of less than 10% for the zircon younger than 500 Ma and less than 5% for the zircon older than 500 Ma. All the ages and isotope results of the LA–ICP–MS zircon U–Pb analysis are listed in Supplementary Table S1 (available online from https://doi.org/10.2465/jmps.200916).

RESULTS

Analytical age data and sample descriptions of three samples are summarized in Table 1. Most of the zircon grains from three samples show clear oscillatory zoning as evidenced by the SEM–CL images (Fig. 3). The majority of the zircon grains in sample KTM–Qtz1814 and KTM–Ss1923 are transparent and colorless, however, the zircon grains in KTM–Qtz1818 generally show brown color.

Metamonzite (KTM–Qtz1814) and sandstone (KTM–Ss1923) show the most significant age clusters at Permian to Triassic age (Figs. 4b and 4f). 86% of the zircon grains in KTM–Qtz1814 yield the age value around 300–230 Ma and 47% of the zircon grains in KTM–Ss1923 display the age ranging between 270–230 Ma (Table 1 and Figs. 4b and 4f). Among them, the sample KTM–Ss1923 shows the single peak age at around 232 Ma (Fig. 4f). On the other hand, three minor peaks of at around 285, 258, and 237 Ma can be found from the sample KTM–Qtz1814 which corresponds to the Permian to Triassic age (Fig. 4b). The youngest detrital zircon grains of both samples are 228.3 ± 11.7 Ma for KTM–Qtz1814.

![Figure 3. CL image of the typical zircon grains of the studied samples. (a) Metamonzite sample KTM–Qtz1814. (b) Metamonzite sample KTM–Qtz1818. (c) Sandstone sample KTM–Ss1923. Each LA–ICP–MS analyzed spot is labeled with the concordant age values together with the 2σ error and the Th/U ratio. 206Pb/238U ages are used for the zircon younger than 1000 Ma, while 207Pb/206Pb ages are used for the zircon older than 1000 Ma.](https://doi.org/10.2465/jmps.200916)
(Table 1 and Fig. 4b) and 226.0 ± 9.1 Ma for KTM–Ss1923 (Table 1 and Fig. 4f), indicating their maximum depositional ages. Hence, both rocks are considerably deposited in the Late Triassic age. Additionally, both samples have a secondary age cluster at Early Paleozoic (Figs. 4b and 4f). Three zircon grains (7%) show the ages between 480–450 Ma for KTM–Qtz1814, while 31% of the zircon grains show the ages at around 480–400 Ma for KTM–Ss1923 (Table 1 and Figs. 4b and 4f). These two samples indicate the conspicuous absence of the 400–320 Ma zircon grains. Most of the zircon grains from KTM–Qtz1814 and KTM–Ss1923 show the Th/U ratios higher than 0.1 (Fig. 5).

Contrary to the metaquartzite (KTM–Qtz1814) and sandstone (KTM–Ss1923), metaquartzite (KTM–Qtz1818) does not have any Permian–Triassic zircon grains (Fig. 4d). This sample shows the most significant age cluster at late Paleoproterozoic (peak age of 1780 Ma) (Fig. 4d). Although one grain in the metaquartzite sample (KTM–Qtz1818) shows the remarkable young age of 413.6 ± 16.0 Ma, this is considered as a metamorphic age as evidenced from the extremely low Th/U ratio
of the zircon as 0.01 (Fig. 5). Also, the lower intercept of the Tera–Wasserburg Concordia diagram likely tends to be at around 400 Ma (Fig. 4c). Hence, this sample was considered to be metamorphosed at around 400 Ma. The Archean to early Paleoproterozoic detrital zircon only found in this metaquartzite sample (KTM-Qtz1814) (Fig. 4d). 16% of the detrital zircon grains in this sample show Archean age and the oldest detrital zircon marks a Paleoarchean age (207Pb/206Pb age of 3314 ± 22 Ma). The youngest detrital zircon of this sample shows the 207Pb/206Pb age of 1359 ± 85 Ma (Th/U = 0.55) (Table 1 and Figs. 4b and 4f), which can be regarded as the age of maximum deposition.

A small peak of early Mesoproterozoic can be found in metaquartzite (~ 1435 Ma: KTM-Qtz1814) and sandstone (~ 1445 Ma: KTM-Ss1923) (Figs. 4d and 4f). Neo-proterozoic zircon grains are only found in KTM-Ss1923 as a 6% concentration, however, they show scattered ages without any cluster (Fig. 4f).

**DISCUSSION**

**Phanerozoic magmatic-metamorphic-tectonic events of the Kontum Massif and southern part of the Truong Son Belt**

Recent geochronological studies have revealed two significant igneous and metamorphic activities of the Kontum Massif and the Truong Son Belt, one at Early Paleozoic (e.g., Nagy et al., 2001; Nakano et al., 2007; Roger et al., 2007; Usuki et al., 2009; Nakano et al., 2013; Hieu et al., 2016; Minh et al., 2020a; Bui et al., 2020), and the other at Permian–Triassic time (e.g., Nakano et al., 2009; Nakano et al., 2013; Hieu et al., 2015; Owada et al., 2016; Bui et al., 2020). Most of the magmatic and metamorphic rocks of the Kontum Massif and the Truong Son Belt were formed during these two tectono-thermal events. Our detrital zircon data of metaquartzite (KTM-Qtz1814) and sandstone (KTM-Ss1923) from both blocks record these two age peaks (Figs. 4b and 4f). The maximum depositional timing of both rocks can be approximated as Late Triassic (228 Ma for KTM-Qtz1814 and 226 Ma for KTM-Ss1923) from the youngest detrital zircon grains (Figs. 4b and 4f). The detrital zircon age spectra of two samples display the distribution of surface-exposed rocks in the Kontum Massif and southern part of the Truong Son Belt at Late Triassic time after the continental collision event between the Indochina and South China blocks. A minor amount of Precambrian zircon grains from the Early Triassic metaquartzite in the Kontum Massif (KTM-Qtz1814; Fig. 4b) indicates that the surface exposure of Precambrian rocks was limited at the Late Triassic time, instead, the Permian–Triassic, as well as the Early Paleozoic rocks occupied a major part of the Kontum Massif on the present-day erosional level. In contrast, Late Triassic sandstone in the southern part of the Truong Son Belt has i.e., 20% of Precambrian zircon grains (Fig. 4f). The Precambrian basement rocks or re-worked zircon grains from the Paleozoic strata might have supplied the Precambrian zircon grains to the Late Triassic sedimentary basin (Nong Son Formation) in the southern part of the Truong Son Belt.

The Permian–Triassic zircon components of KTM-Qtz1814 and KTM-Ss1923 are 86 and 47% respectively, which represent the most prominent age population (Table 1 and Figs. 4b and 4f). The Early Paleozoic age components of zircon grains of KTM-Qtz1814 and KTM-Ss1923 are 7 and 31%, respectively, and those form the second-largest population (Table 1 and Figs. 4b and 4f). Both rocks show the lack of the 400-320 Ma zircon grains, which can be explained by several scenarios, viz., the absence of the significant orogenic events in this period, blocking of the supply source of the detritus, or the source rocks not yet been exposed at the erosional surface during the Late Triassic time, when the two rock layers were deposited. Modern river sand zircon in the Kontum area also revealed its spectral pattern as the most significant population of Permian–Triassic (270–211 Ma), as well as the minor amount of Early Paleozoic (455–424 Ma), Precambrian, and mid–Cretaceous ages (Hung et al., 2019). Except for the Cretaceous zircon grains, they show a good coincidence with the metaquartzite (KTM-Qtz1814) in the Kontum Massif as well as the sandstone (KTM-Ss1923) in the southern part of the Truong Son Belt (Figs. 4b and 4f). This similarity implies that no significant modification events were proceeded from Triassic to the present time in the Kontum Massif except the
small input of mid-Cretaceous magmatic products.

Among the Permian-Triassic age clusters of metaquartzite (KTM-Qtz1814) from the Kontum Massif, three significant age peaks can be recognized at around 285, 258, and 237 Ma (Fig. 4b). These multiple peaks may display the presence of multi-stage magmatic-metamorphic-tectonic activities caused by the continental collision process. Hieu et al. (2017) reported the presence of the arc igneous activity formed by the oceanic subduction at ~ 290–260 Ma, before the continental collision stage between the Indochina Block and the South China Block. Wang et al. (2018) indicated that the Permian–Triassic igneous activity along the Indochina–South China collision belt can be classified as arc-related magmatism at ~ 247 Ma, syn-collisional magmatism at 247–237 Ma, and subsequent post-collisional magmatism at 237–200 Ma. Besides, Hieu et al. (2020a) summarized the collision-related magmatism as the subduction-related stage (290–260 Ma), syn-collisional stage (250–240 Ma), and post-collisional stage (240–210 Ma). Based on these subdivisional tectonic interpretations, most of the Permian magmatic products were formed as a result of the subduction-related tectonism. Therefore, the older peaks of ~ 285 and ~ 258 Ma in metaquartzite (KTM-Qtz1814) coincide with the subduction-related magmatism which occurred before the continental collision event. The subduction polarity of the Paleo-Tethys Ocean before the collision of the Indochina Block and the South China Block is still under debate with the double-sided subduction model (e.g., Xia et al., 2020; Xu et al., 2020; Nakano et al., 2021) and the single-sided subduction model (e.g., Thanh et al., 2019).

Although the reports of the Permian magmatic products are insufficient from the Kontum Massif, e.g., zircon U-Pb ages of 306–278 Ma from the Ben Giang–Que Son Complex (Sang, 2011; Fig. 1b), together with the existence of the Permian magmatic rocks and the abundant Permian detrital zircon grains from the present study (Fig. 4b), we emphasize that the subduction-related magmatism played an important role in the growth of the Kontum Massif. Although the double-side subduction of the Paleo-Tethys Ocean under both the Indochina and South China blocks is unlikely considering the present tectonics, at least the subduction under the Indochina Block side had occurred. Younger peaks of 237 Ma for KTM-Qtz1814 (Fig. 4b) and a significant cluster of 232 Ma for KTM-Ss1923 (Fig. 4f) may coincide with the syn-collisional to post-collisional magmatic activities.

**Supracrustal evolution of the Kontum Massif**

In contrast to the detrital zircon spectra of the two Triassic (meta)-sedimentary rock samples (KTM-Qtz1814 and KTM-Ss923), detrital zircon grains of the metaquartzite (KTM-Qtz1818) do not reflect the two main Phanerozoic orogenic events of the Indochina Block. Instead, metamorphic zircon grains (~ 414 Ma) and the discordant data points display the Early Paleozoic metamorphism (Figs. 4c and 5). No Permian–Triassic metamorphic events are recorded in zircon grains. The approximated maximum depositional age of this sample is ~ 1359 Ma based on the youngest detrital zircon (Table 1 and Fig. 4d). The absence of the detrital zircon grain younger than 1359 Ma in sample KTM-Qtz1818 (Fig. 4d) indicated that the protolith of metaquartzite might have been deposited in Meso- to Neoproterozoic age. The present study reports one of the oldest cratonic cover sequence (metaquartzite; KTM-Qtz1818) in the Kontum Massif. Among the Asian continental blocks identified so far, ancient (i.e., Archean to Paleoproterozoic) basement rocks are limited and mainly distributed in the North China Block (e.g., Zhao and Cawood, 2012; Zhao and Zhai, 2013) and the South China Block (Yangtze Block; e.g., Guo et al., 2015). Thus, the present study reveals that the Kontum Massif preserves one of the oldest records of detrital evidence in the Southeast Asian continent.

The age spectra of metaquartzite (KTM-Qtz1818) in the Kontum Massif records a geological history before the Early Paleozoic event. The most prominent age peak of metaquartzite (~ 1780 Ma; KTM-Qtz1818) documents the significant contribution of late Paleoproterozoic crustal materials to generate the supracrustal rocks of the Kontum Massif (Fig. 4d). The Archean to late Paleoproterozoic detrital zircon grains (up to 3314 Ma; Fig. 4d) illustrate that the ancient (i.e., Archean) crustal materials also played an important role in the generation of the quartzite in the Kontum Massif as a provenance of detritus. In addition, a small peak of early Mesoproterozoic (~ 1435 Ma) detrital zircon grains can be found from metagraywacke (KTM-Qtz1818; Fig. 4d). The Mesoproterozoic ages were previously reported from the zoned zircon core (Nam et al., 2001) and monazite (Nakano et al., 2013) from the Kontum Massif. Besides, the most recent study revealed the ~ 1450 Ma igneous rocks as a protolith of the Triassic metamorphic rocks in the Kontum Massif (Nakano et al., 2021). Nakano et al. (2021) further concluded that the ~ 1450 Ma is an initial stage of the formation of the Kontum Massif (Indochina Block) possibly formed under the oceanic arc environment based on the Hf isotopic analysis of zircon grains. Mesoproterozoic age peak from the present study shows a good coincidence with the expected thermal event of the Kontum Massif (Fig. 4d). According to the compiled detrital zircon data from the Indochina Block, the Mesoproterozoic population (~ 1450–1430) is a unique event in the Kontum Massif.
Although the detrital zircon age spectra of Silurian metamorphic rock do not have a Mesoproterozoic zircon (Fig. 6b; Nakano et al., 2021), this can be explained by the difference of the depositional timing. The detrital zircon age spectra from the Triassic metamorphic rocks in the Kontum Massif show a large population in the Late Mesoproterozoic to Early Neoproterozoic time with the ~ 1430 Ma small peak (Fig. 6c). This age spectra (Fig. 6c) show the large contrast between older rocks (i.e., Meso- to Neoproterozoic supracrustal rock) in the Kontum Massif (Figs. 6a and 6b). The remarkable spectral change found in the Kontum Massif indicates the significant input of the Late Mesoproterozoic to Early Neoproterozoic crustal materials to generate the supracrustal rocks in the Kontum Massif (Figs. 6a–6c).

In contrast to the Kontum Massif, the detrital zircon age spectra of Early Paleozoic sedimentary rocks in the Truong Son Belt document the most prominent age peak of earliest Neoproterozoic (~ 970 Ma), and latest Archean to earliest Paleoproterozoic ages (around 2500 Ma), with the absence of ~ 1780 and ~ 1450–1430 Ma prominent peaks (Fig. 6d). Although the Triassic metamorphic rocks in the Kontum Massif are characterized by the large input of the Late Mesoproterozoic to Early Neoproterozoic crustal materials, the age spectra between both massifs (belts) show the deferent pattern (i.e., the existence of 1430 Ma peak, which is a unique event in the Kontum Massif; Figs. 6c and 6d). These contrasting patterns indicate the different crustal source provenances of the sedimentary basins in the Kontum Massif and the Truong Son Belt. The Tam Ky–Phuoc Son suture zone divides both massifs (belts) (Fig. 1b). The geotectonic character of the Tam Ky–Phuoc Son suture zone is still unclear, and some tectonic models have been proposed. One is the Early Paleozoic continental collision model along the Tam Ky–Phuoc Son suture zone (e.g., Faure et al., 2018; Jiang et al., 2020). Based on this model, both sides of the suture zone had been developed as different geotectonic blocks before the amalgamation of the Kontum Massif and the Truong Son Belt. However, other groups had pointed out that the Early Paleozoic magmatic–metamorphic rocks were formed under the continental arc tectonism at the South China Block side (e.g., Nakano et al., 2013, 2021). Present study together with the previously reported data documents the different source rock provenance between the Kontum Massif and the Truong Son Belt (Figs. 6a–6d). This difference may reflect the different evolutionary histories of the Kontum Massif and the Truong Son Belt before the Early Paleozoic amalgamation along the Tam-Ky Phuoc Son suture zone.

The detrital zircon of the latest Paleoproterozoic to earliest Mesoproterozoic rocks in the southwestern Yangtze Block, a part of the present South China Block (Fig. 1a), revealed in the earlier studies documented the multiple prominent events of ~ 2700, 2300, 1840, with 1745 Ma (Zhao et al., 2010; Wang and Zhou, 2014; Liu et al., 2018; Fig. 6e). Particularly, one of the prominent age peaks of sedimentary rocks in the southwestern Yangtze Block can be seen at ~ 1900–1700 Ma, which
coincides with the age spectra of metaquartzite (KTM-Qtz1818) in the Kontum Massif (Figs. 6a and 6e). However, the older significant peak in the southwestern Yangtze Block (~ 2700 Ma) cannot be seen in our studied metaquartzite (KTM-Qtz1818, Fig. 6a). In conclusion, the Kontum Massif was developed as a different Massif from the southwestern Yangtze Block as well as the Truong Son Belt during the Precambrian period before their amalgamation.

CONCLUDING REMARKS

1. Detrital zircon age spectra of quartzite in the Kontum Massif and sandstone in the southern part of the Truong Son Belt confirm the existence of two tectono-magmatic-metamorphic events of the latest Carboniferous to Triassic (~ 300–230 Ma) and the Early Paleozoic (~ 480–410 Ma). The abundant Permian detrital zircon grains from the Late Triassic metaquartzite in the Kontum Massif document that the subduction-related magmatism played an important role in the growth of the Kontum Massif.

2. Detrital zircon age spectra of the metaquartzite documents the remarkable Paleoproterozoic (~ 1780 Ma) population as well as early Mesoproterozoic (~ 1435 Ma) and scattered Archean grains. The protolith of metaquartzite was deposited probably in Mesoproterozoic time. The Archean to early Paleoproterozoic zircon grains in this metaquartzite document the contribution of the Archean to early Paleoproterozoic crustal materials to deposition of the supracrustal sequence of the Kontum Massif.

3. The Kontum Massif had developed as a different unit from the Truong Son Belt as well as the southwestern Yangtze Block due to their different Precambrian source provenance.

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SUPPLEMENTARY MATERIALS

Color version of Figures 1, 2, 4, and 6 and Supplementary Table S1 are available online from https://doi.org/10.2465/jmps.200916.

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