

# Early Triassic Tectonic Evolution of the Northeastern Kontum Massif: New Constraints from the S-type Granite in Ba To Area, Quang Ngai Province, Central Vietnam



Ha Thanh Tran , Bui Vinh Hau, Ngo Xuan Thanh, Nguyen Huu Hiep, and Ngo Thi Kim Chi

**Abstract** The granitoids exposed in Ba To area, northeastern portion of the Kontum Massif, central Vietnam were previously assigned as part of the Hai Van complex. Field investigation and petrographic study reveal that the magmatic rocks in Ba To area comprise dominantly medium- to coarse-grained, per-aluminous two-mica granite of S-type origin. These rocks are strongly overprinted by several phases of tectonic activities including the emplacement of felsic and mafic dikes and veins, formation of weak ductile foliation, brittle fracturing, and widespread alteration under the influence of several post-magmatic thermotectonic processes. Results of U–Pb dating of zircons collected from granite in Ba To area show a crystallization age of  $245.8 \pm 1.5$  Ma for the magmatic rock. The petrographic study and absolute age dating results conducted by this work are comparable to other recent works on similar granitoid occurred in the northern margin of the Kontum Massif. This indicates that the widespread Ca 245 Ma Hai Van-type S-type granitoid along the north and northeastern portions of the Kontum Massif were derived from a collisional orogenic event, which extended from Late Paleozoic onward during the assembly of Sibumasu Block to Indochina Block to form the Proto-Southeast Asia, which is correspondent to the Indosinian Orogeny. Several post-intrusive thermotectonic events due to the tectonic activities along the newly formed Proto-Indochina Block

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had resulted in subsequent deformation, injection of late magmas and alterations of the Hai Van—Type magmatic rocks.

**Keywords** Kontum Massif · Hai Van Complex · Granitoid · U-Pb zircon age

## 1 Introduction

The Indochina Block, a major tectonic entity of mainland Southeast Asia, comprises of two main components: Truong Son Belt and Kontum Massif [1–3]. The Kontum Massif, which forms the core portion of the Indochina Block (Fig. 1), is mainly composed of high-grade metamorphic rocks and grouped into different units including Kannack, Ngọc Linh, and Kham Duc complexes [1]. These metamorphic rocks were intruded by voluminous magmatic suites of different ages and origins [1, 4] (Fig. 1). Previous studies suggested that magmatic rocks in the Kontum Massif have multi-origins with ages are variable from Archean to Late Proterozoic, Paleozoic to Mesozoic [1, 2, 4, 5], which are tectonically intercalated and formed complex exposures of many types of rocks in the same area. Because of that complex spatial distribution, many magmatic bodies of different ages and origins were doubtfully identified that they had been derived from the same magmatic source and age, which had been grouped into a single magmatic complex in previous mapping without understanding of the absolute age and tectonic environment related to magma emplacement. Such inadequate interpretation has led to unconvincing reconstruction of the regional tectonic evolution of the Kontum Massif.

In order to distinguish magmatic complex of different ages and origins in an area, in addition to field studies to determine the spatial relationship and relative timing of the magmatic suites, an important factor is to perform absolute age dating of the magmatic rocks in a synchronous and systematic manner. For this approach, this study had conducted field mapping in Ba To area, Quang Ngai Province, which occurs in the northeastern part of Kontum Massif (Fig. 1), where magmatic intrusive rocks are widely exposed and is formerly classified as a part of the Hai Van Complex of Late Triassic age [e.g., 1, 4] (Fig. 1). During the mapping, samples had been collected to determine the absolute crystallization age of the observed magmatic rocks in this area using U–Pb isotopes in zircons by LA-ICP-MS technique. This paper presents new results on the crystallization ages of the samples from S-type magmatic rocks and, in conjunction with available geological data, discusses this new finding in the framework of regional tectonic evolution.

## 2 Geological Background

The Ba To area is located in Quang Ngai Province and forms part of the northeastern portion of the Kontum Massif (Fig. 1). The area is underlain by a lithologically and

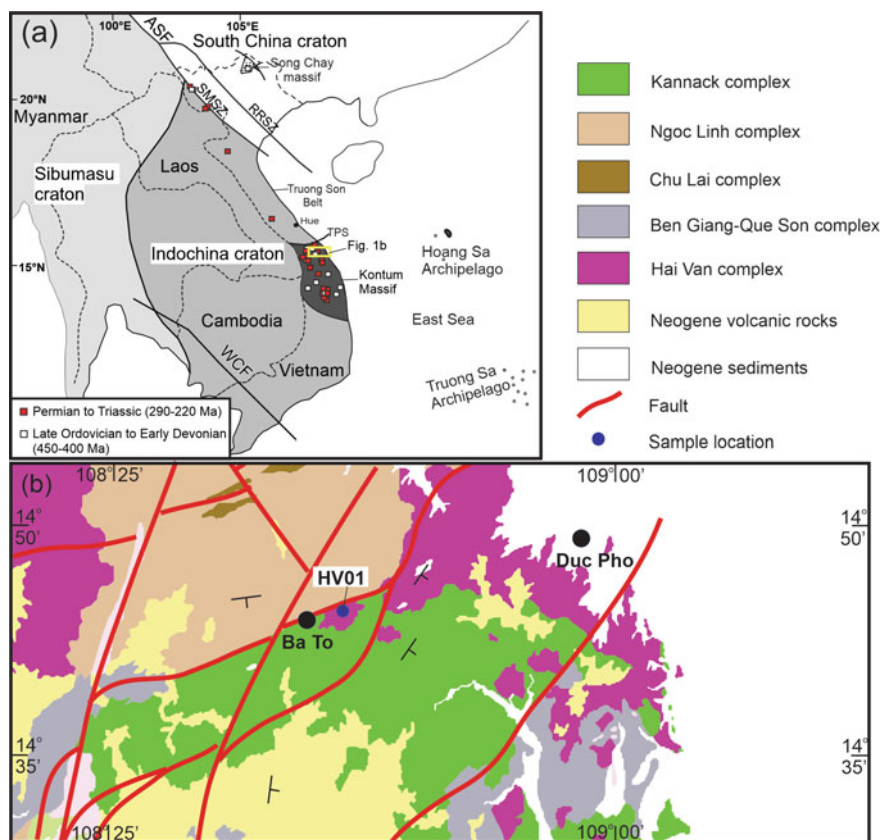


**Fig. 1** **a** Location of study area in Vietnam and generalized tectonic map of part of Southeast Asia [6] showing the relative position of Indochina Block, Kontum Massif and the study area; **b** generalized geological map of the study area (compiled from various sources) and location of sampling for this study. Abbreviations in Fig. **a**: *ASF* AilaoShan Fault; *SMSZ* Song Ma Suture Zone; *RRSZ* Red River Shear Zone; *TPS* Tam Ky-Phuoc Son Suture Zone; and *WCF* Wang Chao Fault

structurally complex basement (Fig. 1b), indicated by abundant high-grade metamorphic assemblages, multiple magmatic complexes, and sedimentary cover of differing ages and origins [e.g., see 1, 4].

The high-grade rocks of the Kannack complex exposes in the southern part of the Ba To area (Fig. 1b), mainly comprises of high temperature to ultrahigh temperature (UHT) granulite-facies and minor amphibolite-facies rocks, which are predominant pelite with intercalated minor amounts of mafic and calc-silicate rocks [7, 8]. Intrusive rocks including granitoid and gabbroic bodies that are exposed as stocks and lenses within granulite-facies metamorphic rocks [9]. The peak metamorphic condition of the granulites in the Kannack Complex estimated as 800–1000 °C and 8–11 kbar [10, 11]. The age of this complex was suggested to be Archean to Paleoproterozoic [1, 4, 12, 13]. Recent studies have suggested that the formation age of

this complex may be Paleoproterozoic, which then affected by poly-metamorphism during Mesoproterozoic, Ordovician and Late Permian–Triassic [1].

The northern flank of the Kannack Complex is bounded by the amphibolite-facies felsic mylonite, pelitic gneiss, and mafic granulite that are grouped into Ngoc Linh Complex [1]. The mafic granulite is commonly occurred as boudinaged blocks or lenses within mylonitized felsic gneisses or as disrupted bodies intercalated with felsic and pelitic gneisses [10]. The amphibolite-facies metamorphism of the Ngoc Linh Complex was formed under the temperature and pressure condition estimated as 700 °C and 5 kbar respectively [10].

The geochronological studies for the rocks of Kannack and Ngoc Linh complexes show confusing results from Archean age (2541 Ma, U–Pb age from core of zircon crystals) to Early Triassic age [1, 14, 15], leading to a major argument on the formation ages of these complexes. There was suggestion that these complexes had undergone multiple thermal history including high-grade, high temperature-medium pressure metamorphism at ca. 450 Ma and overprinted by regional metamorphism and deformation during Permian–Triassic [1, 16–18].

The Kannack and Ngoc Linh complexes within the study area are intruded by numerous igneous bodies of differing age and origins, which have been grouped into several complexes including Nam Nin and Ta Vi complexes (Proterozoic), Chu Lai-Ba To Complex (Early Middle Paleozoic) or Hai Van Complex (Late Triassic; [1]).

The Nam Nin and Ta Vi complexes consist of mainly plagiogranite, tonalite, medium-coarse grain sized gabbro amphibolite bodies that are scatted and intercalated with the high-grade metamorphic rocks of either Kannack or Ngoc Linh complexes. Although had been considered Proterozoic in age in previous works, the absolute age and origin of these rocks remain uncertain.

The Chu Lai-Ba To Complex comprises of batholith-style and smaller bodies of predominantly coarse-grained granitoid, which were strongly deformed and intercalated with high-grade rocks of the Kannack and Ngoc Linh complexes. Previous studies suggested that the Chu Lai-Ba To-type rocks were intruded in Late Proterozoic [4, 12]. Recent studies, however, have showed that the crystallization age of this complex occurred adjacent to this study area is much younger, at about 440–430 Ma on the basis of U–Pb zircon dating [e.g., 19, 20].

Late Paleozoic intrusive rocks are abundantly exposed in the eastern and south-eastern part of the study area (Fig. 1), comprising dominantly mica-rich S-type granitoid containing numerous inclusions of surrounding sedimentary and/or metamorphic rocks that are assigned to the Hai Van Complex (e.g., see [1] for discussion). Previous studies suggested that the age of Hai Van Complex is Late Triassic [1]. Recent studies in adjacent areas show that part of Hai Van Complex have various ages, ranging from 245 to 290 Ma [2, 5, 21]. This indicates that the classification intrusive rocks with different ages and origins into a single complex is unconvincing without detailed studies on geochronology and geochemistry.

### 3 Sample Collection and Analytical Methods

#### 3.1 Sample Collection

In the study area, magmatic rocks that were mapped as a part of the Hai Van Complex are exposed as a large body in the northeast of the study area, with the biggest body is exposed as several tens of square kilometers in size and many smaller bodies that are intruded into, and scattered within, the high-grade rocks of the Kannack and Ngoc Linh complexes (Fig. 1b).

Several samples had been collected from medium grained granite that exposed near Ba To Town, Quang Ngai Province (14°45'160" N and 108°42'522" E (Fig. 1b) for petrographic study and absolute U–Pb zircon dating.

#### 3.2 Analytical Methods

The collected samples were prepared for thin sections for petrographic analysis and separation of zircons for U–Pb dating at the Centre for Excellence in Analyses and Experiments (CEAE) of the Hanoi University of Mining and Geology.

A sample (HV01) was chosen for collection of zircon grains by conventional method [22] including grinding, washing, and separation by using heavy liquid and Franz magnetic separator before hand-picked, mounted in epoxy resin prior to polishing to expose the interior of the zircon crystals.

Cathodoluminescence (CL) images were taken to examine zircon morphology, internal textures and to guide spot selections for the U–Pb analyses. The U–Th–Pb isotopic compositions of zircons from sample HV01 were measured using Nu Plasma II multicollection inductively coupled plasma mass spectrometer equipped with a New Wave Research 193 nm ArF excimer Laser Ablation system (LA-MC-ICP-MS) housed at the Ochang Campus of the Korea Basic Science Institute (KBSI). The Nu Plasma II mass spectrometer contains fixed collectors of sixteen Faraday detectors and five ion-counting electron multipliers. The collectors were set to simultaneously detect for U–Pb age determination in the following array:  $^{202}\text{Hg}$  (IC 4),  $^{204}(\text{Hg} + \text{Pb})$  (IC 3),  $^{206}\text{Pb}$  (IC 2),  $^{207}\text{Pb}$  (IC 1),  $^{208}\text{Pb}$  (IC 0),  $^{232}\text{Th}$  (high 7), and  $^{238}\text{U}$  (high 9), respectively.  $^{235}\text{U}$  was calculated from the signal at mass  $^{238}\text{U}$  using a natural  $^{238}\text{U}/^{235}\text{U} = 137.88$ . Mass number 204 was used as a monitor for common  $^{204}\text{Pb}$  after discarding the  $^{204}\text{Hg}$  background. All analyses were carried out with a spot size of 20  $\mu\text{m}$  in diameter, 5 Hz repetition rate, and energy density of 3 J/cm<sup>2</sup>. He (940 ml/min) was used as carrier gas. Background intensities, dwell time, and wash out time were measured as 30 s, 30 s, and 20 s, respectively. A Time Resolved Analytical (TRA) procedure was employed to monitor the measured isotope ratio. Signal intensities for each collector were collected every 0.2 s (integration time). Raw data were corrected for the background, laser-induced elemental fractionation, mass discrimination, and drift in ion counter gains. U–Pb isotope ratios were calibrated by

concordant reference zircons 91,500 (1065 Ma) [23] and Plešovice zircon ( $337.13 \pm 0.37$  Ma) [24] that was used at the beginning and end of each analytical session, and at regular intervals during each session, using protocols adapted from [25] a correlation of signal vs. time was also assumed for the reference zircons. The Iolite software running in IgorPro (WaveMetrics, Inc; [www.wavemetrics.com](http://www.wavemetrics.com)) was used for the data reduction of LA-MC-ICP-MS analyses. Once processed with Iolite, the data were exported in EXCEL, and Isoplot [26] was used to calculate weighted average ages and make Tera-Wasserburg plots.

## 4 Analytical Results

### 4.1 Petrography

The studied rocks are medium to coarse grained, non to weakly sparsely foliated, dark-gray granite with minor late pegmatite, aplite and quartz veins intruded and/or filled the fractures within the rocks (Fig. 2a–c). In part, the pegmatic and quartz dike and veins are flattened and reoriented sub-parallel to the foliation (Fig. 2b), whereas the aplitic veins are either irregular or fracture-filling (Fig. 2c). The mineral composition of the rocks mainly comprises of plagioclase (40%), K-feldspar (35%), quartz (10–15%), muscovite and biotite (~5%), and other minor minerals (Fig. 2d). The mineral composition of the granitic rocks in this area indicate that they are peraluminous S-type granite, possibly derived from syn-orogenic collisional setting. In this area, the rocks had undergone a post-crystallization deformation and alteration, indicated by the fracturing of the mineral grains, undulose extinction and widespread of alteration rims around the K-feldspar and plagioclase grains (Fig. 2d).

Both the field investigation and thin section interpretation indicate that the granitic rocks in the study area had undergone a complex post-intrusive history, including an early veining, which led to the intrusion of felsic (pegmatite) dikes/veins followed by a phase of regional deformation to produce overprinting foliation and recrystallization, brittle fracturing, intrusion of late aplitic veins, and hydrothermal alteration.

### 4.2 U–Pb Dating of Zircons

Zircon crystals from granitic rocks collected in this study are commonly 70–200  $\mu\text{m}$  in the longest dimension, with euhedral to subhedral morphology, and their length-to-width ratios from 2:1 to 3:1 (Fig. 3). Some zircon crystals exhibit core–mantle structure in CL images and all the zircon grains show well-developed oscillatory zoning.

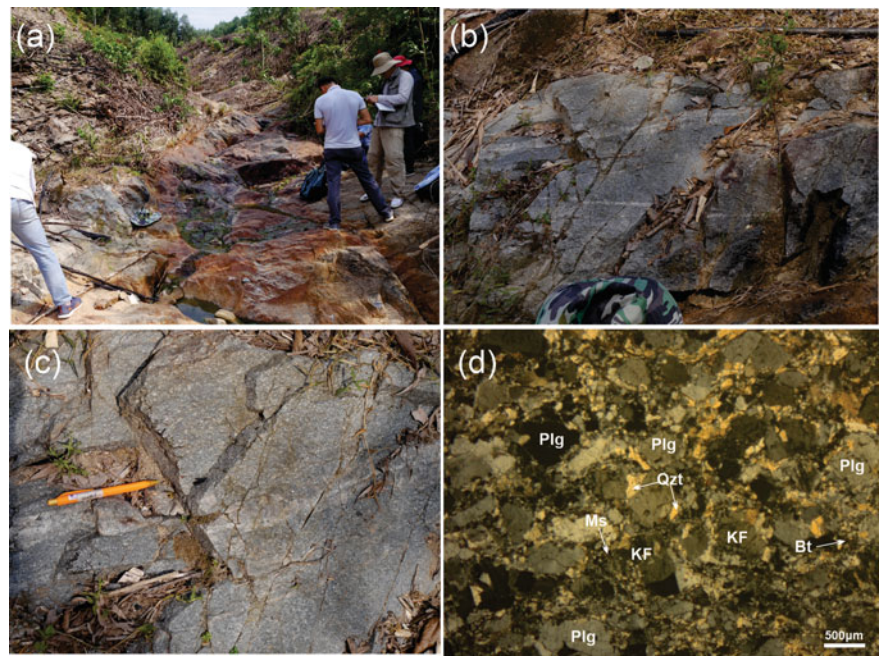
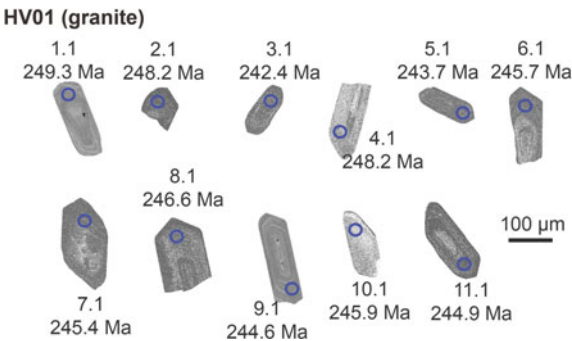


**Fig. 2** a–c Field exposure of the granitic rocks in the study area, east of Ba To town. In places, the rocks are weakly foliated with sub-parallel alignment of pegmatite/quartz veins (b). In places, the main rocks are intruded by several generations of veins with differing composition (felsic or mafic dikes and veins, c), or cut by brittle structures (b, c). d is the photograph of the rocks under thin section, which shows post-intrusive recrystallization indicated by undulose extinction of the quartz. Late hydrothermal alteration is indicated by the pale reaction rims around the K-feldspar and plagioclase crystals. The observed petrological and structural relationship indicate a complex intrusive and post-intrusive tectonic history (see text for discussion). Abbreviations: *Plg* plagioclase, *KF* K-feldspar, *Ms* muscovite, *Bt* biotite, *Qzt* quartz

**Fig. 3**  
Cathodoluminescence (CL) image of the representative zircon grains used for U–Pb analysis with positions of analytical points (in circles) and their determined ages from sample HV01



The U–Th–Pb isotopic compositions of zircon were presented in the Table 1 and plotted in the Tera–Wasserburg concordia and Weighted mean age diagrams (Fig. 4). The U–Th–Pb isotopic analyses result show that U and Th contents range from 289 to 4590 ppm and 229 to 4049 ppm, respectively. Whereas the Th/U ratios of the analyzed zircon crystals range from 0.62 to 1.08 (Table 1), which strongly demonstrate a direct crystallization of the zircon from a magmatic source [27].

The most suitable  $^{238}\text{U}/^{206}\text{Pb}$  age results were corrected using the  $^{207}\text{Pb}$  correction by Isoplot 3.6 software (Ludwig 2008) with an error of 2-sigma show the  $^{238}\text{U}/^{206}\text{Pb}$  age varies from 242.4 to 249.3 Ma (Table 1). In the Tera–Wasserburg Concordia diagram, eleven analyses from eleven zircon crystals have well-concordant  $^{238}\text{U}/^{206}\text{Pb}$  age (Fig. 4a). Eleven analyses yield a weighted mean  $^{238}\text{U}/^{206}\text{Pb}$  age of  $245.8 \pm 1.5$  Ma (MSDW = 0.62, probability = 0.80) (Fig. 4b). This age is interpreted as the crystallization age for the granitic rocks in the study area.

## 5 Discussions

The U–Th–Pb zircon ages obtained from this work shows that the crystallization age of the granitoid in the study area is  $245.8 \pm 1.5$  Ma (ca. 246 Ma). If these rocks are part of the Hai Van Complex, it can be confirmed that the age of this Complex in the study area is ca. 246 Ma.

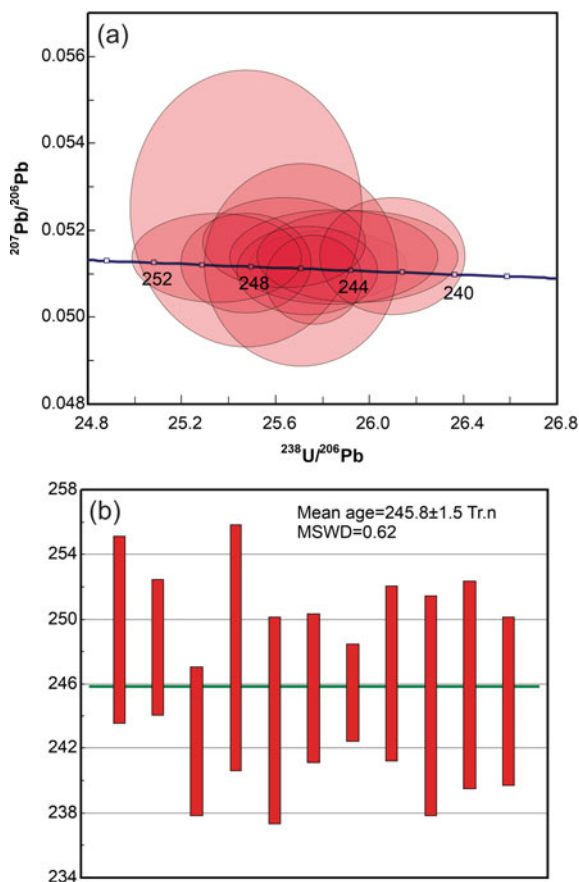
According to previous geological studies, the granitoid assigned to Hai Van Complex is considered to be Late Triassic in age [1, 28]. However, the previous isotopic ages dated by different methods gives confusing ages of the Hai Van Complex, such as  $138 \pm 4$  Ma [29],  $220 \pm 4$  Ma by K/Ar method [30],  $236 \pm 4.6$  Ma [31] by Rb–Sr method. More recently, new results by U–Pb dating (conventional, SHRIMP or LA-ICP-MS) performed on granitoid considered as parts of the Hai Van Complex, which occur along the northern margin of the Kontum Massif, have provided a wide range of ages, from 245 to 290 Ma [2, 5, 21].

The new dating results from this study is in accordance with the ca. 245 Ma crystallization ages obtained elsewhere along the northern margin of the Kontum Massif [2, 5, 21] but differs from other dating results. The different age ranges obtained by different methods and varied across the areas can be explained by several facts: (i) the precision of dating methods used; (ii) the Hai Van Complex was subjected to strong and spatial variable hydrothermal alteration or recrystallization during post-magmatic metamorphic and hydrothermal alteration events. These would lead to the incomplete conservation of the K–Ar or Rb–Sr isotopic system (low closure temperature isotope systems) so that the dating by K–Ar and Rb–Sr or U–Pb methods produce different age values for the same rocks that have experienced different degree of post-intrusive deformation and associated metamorphic and/or alteration; or (iii) the rocks assigned to the Hai Van Complex at different localities within the Kontum Massif are in fact derived from differing magmatic sources that were generated at different time frames and tectonic setting during the regional tectonic evolution.

**Table 1** Results of U-Th-Pb isotopic analyses by LA-MC-ICP-MS performed on zircons of sample HV01 collected from granitic rocks in Ba To area

| No.  | U (ppm) | Th (ppm) | Th/U | Isotopic ratios                  |           |                                 |           | Age (Ma)                        |           |                                  |           |
|------|---------|----------|------|----------------------------------|-----------|---------------------------------|-----------|---------------------------------|-----------|----------------------------------|-----------|
|      |         |          |      | $^{238}\text{U}/^{206}\text{Pb}$ | $2\sigma$ | $^{207}\text{U}/^{206}\text{U}$ | $2\sigma$ | $^{207}\text{U}/^{235}\text{U}$ | $2\sigma$ | $^{238}\text{U}/^{206}\text{Pb}$ | $2\sigma$ |
| 1.1  | 2730    | 2535     | 0.99 | 25.35497                         | 0.295722  | 0.05136                         | 0.00084   | 0.2801                          | 0.0052    | 249.3                            | 2.9       |
| 2.1  | 2478    | 2031     | 0.89 | 25.47771                         | 0.22719   | 0.05124                         | 0.00093   | 0.275                           | 0.0052    | 248.2                            | 2.1       |
| 3.1  | 2150    | 2119     | 1.08 | 26.10285                         | 0.252103  | 0.0514                          | 0.0011    | 0.2718                          | 0.0059    | 242.4                            | 2.3       |
| 4.1  | 383     | 308.1    | 0.89 | 25.47771                         | 0.40245   | 0.0525                          | 0.0026    | 0.283                           | 0.013     | 248.2                            | 3.8       |
| 5.1  | 2460    | 1980     | 0.90 | 25.9538                          | 0.350272  | 0.05139                         | 0.00086   | 0.2756                          | 0.005     | 243.7                            | 3.2       |
| 6.1  | 2860    | 2062     | 0.82 | 25.74003                         | 0.245143  | 0.05107                         | 0.00083   | 0.2765                          | 0.0055    | 245.7                            | 2.3       |
| 7.1  | 1946    | 1023     | 0.62 | 25.76656                         | 0.165979  | 0.05086                         | 0.00083   | 0.2733                          | 0.0046    | 245.4                            | 1.5       |
| 8.1  | 1639    | 1170     | 0.84 | 25.64103                         | 0.282709  | 0.05171                         | 0.00084   | 0.2793                          | 0.0047    | 246.6                            | 2.7       |
| 9.1  | 3799    | 2467     | 0.78 | 25.85315                         | 0.360928  | 0.05138                         | 0.00089   | 0.2756                          | 0.0067    | 244.6                            | 3.4       |
| 10.1 | 289.4   | 229.5    | 0.95 | 25.71355                         | 0.337205  | 0.0512                          | 0.0019    | 0.273                           | 0.01      | 245.9                            | 3.2       |
| 11.1 | 4590    | 4049     | 1.06 | 25.82645                         | 0.273472  | 0.05118                         | 0.00065   | 0.2739                          | 0.0048    | 244.9                            | 2.6       |

**Fig. 4** **a** The Tera-Wasserburg Concordia diagram showing  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{238}\text{U}/^{206}\text{Pb}$  plots for the analytical results for zircon dating show in Table 1, in which most of the ages are concordant and fall in the 242.4–249.3 Ma. **b** The weighted mean age diagram shows absolute ages and SWD of dating results as well as mean age of the zircon grains of sample HV01



They are temporarily grouped in to a magmatic complex during the mapping and other studies based solely on the tentative comparison of petrographic similarity, field occurrence, or relative age dating (e.g., see [5] for detail discussion).

The results of this work and comparable results of similar works conducted recently clearly demonstrate the existence of a regional widespread of ca. 245 Ma magmatic event. This also shows that during Late Paleozoic to Early Mesozoic, the Kontum Massif had experienced a complex thermotectonic history, which led to the formation of multiple magmatic suites of different ages and origins that intruded successively in the same area.

The mineral composition of the granitic rocks in this area shows that they are per-aluminous S-type granite, possibly derived from syn-orogenic collisional setting (see also [32]). The widespread of Hai Van-type, ca. 245 Ma S-type granitoid complexes along the northern margin of the Kontum Massif may indicate that the collisional activities may have taken place since at least Late Permian, leading to the deep burial and melt of the supracrustal materials to form S-type granitic magma that

was widely intruded into the upper crust in this area. This orogenic activity may correspond to the Indosinian orogenic phase, which is directly related to the collision between the Sibumasu and Indochina blocks to create a Proto-Southeast Asia Block, which has been discussed by many recent studies [2, 6, 33–36]. Subsequent tectonic overprinting due to terrane collision and assembly around the Proto-Southeast Asia would have led to the overprinting deformation and alteration of the ca. 245 Ma magmatic rocks in this areas and other parts of the Kontum Massif [2, 6, 35].

## 6 Conclusion

Detailed field investigation, petrographic study, and U–Pb age dating of zircons from the rocks by LA-ICP-MS method for the granitic rocks in the Ba To area, northeastern Kontum Massif has revealed that the Hai Van-type magmatic rocks in this area consists of per-aluminous, S-type granite that was crystallized at ca. 246 Ma and then overprinted by several phases of tectonic activity, including the intrusions of felsic magmas, sub-ductile deformation, brittle fracturing, mafic dikes and veins injection, and hydrothermal alteration. The occurrence of ca. 246 Ma S-type granite in the area as well as widespread exposure of similar Hai Van-type magmatic rocks is correspondent to a phase of Late Paleozoic to Early Mesozoic tectonic collision and regional orogeny that are likely linked to the assembly of Sibumasu Plate to Indochina Block to form the Proto-Southeast Asia mainland, which is equivalent to the Indosinian Orogeny.

The results of this study also show that there is an urgent need for more quantitative and systematic studies on the field occurrence, composition, and age of magmatic rocks, especially in the areas that are multiply and complexly intruded by numerous types of magmas of differing ages and origins that cannot be distinguished based solely on petrographic composition or field appearance. The combination of field studies, chemical and isotopic analysis should be carried out systematically in any mapping and/or regional geological study to precisely determine the age, environment, and nature of the magma evolution as well as its roles in the regional tectonic evolution.

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