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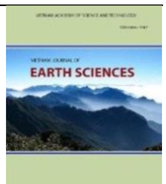

The significance of zircon U-Pb ages in the Ba river basin to the timing of major tectonic stages of Kontum massif

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ABSTRACT

Ba River originates from the Ngoc Linh mountain ranges, NW of Kontum massif and flows into the East Sea from the Da Rang estuary. The Ba River basin (Da Rang river) is considered as the means of transport and storage of products from the Kontum massif resulted following weathering, erosion or deformation processes either by natural causes or the regional thermo-tectonic events. A total of 122 zircon grains separated from the Ba River basin sediments are selected for U-Pb isotopic age dating by LA-ICP-MS method. Among the 122 samples, 114 are concordant, forming 3 major age groups, including middle-Late Cretaceous (105–85 Ma), Middle Permian - Late Triassic (270–211 Ma), Late Ordovician - Early Silurian (455–424 Ma). A few samples show ages scattering from 1470 to 970 Ma (Mesoproterozoic), and one sample shows a value of 2383±24 Ma (Paleoproterozoic). The acquired U-Pb zircon ages may reflect 3 major thermo- tectonic stages in the formation and evolution of the Kontum Massif from the Early Paleoproterozoic till middle-Late Cretaceous, with the most significant time being Middle Permian (270 Ma)-Late Triassic (211 Ma) (97 over 122 samples, e.g., 79,5%), corresponding to the period of convergence, collision and orogeny of the Indosinian block.

Keywords: Zircon U-Pb dating; Kontum massif; Ba River basin; Vietnam Western Highlands.

1. Introduction

1.1. The Kontum Massif

The Kontum massif terrane has been viewed by many researchers as part of Gondwanaland (Tong and Vu, 2005; 2011), the largest crystalline basement exposed to the surface in the Indochina Block. Kontum massif is comprised of igneous-metamorphic formations surrounding a core comprising Archean high temperature-pressure metamorphic rocks (Hutchison 1989). However, up to the present, no age older than

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2500 million years for those supposedly 'Archean' complexes has ever been reported (Tran et al., 2001). In general, Kontum high P-T metamorphic complexes include Kan Nack aged Paleoproterozoic (2500–1600 Ma), Ngoc Linh aged Mesoproterozoic (1600–1000 Ma), (Tran V.T. and Vu K., 2011). The Kan Nack high P-T metamorphic complex forming the core of the Kontum massif was previously classified as Archean on the basis of correlation with typical Archean granulite formations elsewhere in the world (Hutchison, 1989; Tran and Vu, 2011). The surrounding of the "Archean nucleus" is magma-metamorphic complexes aged Paleozoic such as Ta Vi granitoid, Phu My gabbro, Chu Lai granitogneiss, Dai Loc granitogneiss, etc. Other magma-metamorphic complexes of Late Paleozoic-Early Mesozoic include Kon Kbang gabbroic, Ba River enderbite-charnockite, Van Canh granite-granosyenite and Late Triassic lamprophyre dyke complexes, etc. (Tran and Vu, 2011; Tran et al., 1998; 2001; Nagy et al., 2001; Lan et al., 2003; Lepvrier et al., 2007; Pham et al., 2013; Nguyen et al., 2015).

However, recent reported results show that metamorphic activities in the Kontum Terrane were multiple, having occurred in different tectonic periods forming multiple, and overlapping metamorphic facies. The magma-metamorphic activities occurred in the Late Permian-Late Triassic (about 210 Ma) and early Ordovician (about 480–470 Ma), (Tran et al., 2001; 2003) in the Kontum Terrane were so strong that may have erased and assimilated the so-called "Precambrian exhumed basement" following subsequent orogenic and plate collision processes, leading to convergence of Indochina and South China blocks by the end of Late Permian-Early Triassic (Lepvrier et al., 2007; Tran and Vu, 2011). Isotopic age data reported for these thermo-tectonic activities in the Kontum massif have been plentiful (Nagy et al., 2001; Osanai et al., 2001; Tran et al., 2001, 2002; Vu et al., 2013; Pham and Huynh, 2015; Nguyen et al., 2015) (see discussions below).

1.2. Zircon U-Pb dating

Reports on U-Pb dating ages for zircon in sediments and host rocks in large river basins to understand major magmatic and tectonic events in the upstream terrains have been mounting recently (Zhang et al., 2006; Wang et al., 2010; He et al., 2013a; Shao et al., 2016). For example, the Yangtze River initiates from the Tibetan plateau, running more than 6300 km to reach the East China Sea (Chen et al., 2001). With a catchment area of 1.8×10^6 km^2 the river drainage covers several tectonic units, with the Yangtze Craton underlies the main part of the Yangtze River drainage (He et al., 2013b). It has been reported that the relative proportions of different zircon ages in the bedrock of the different tectonic units indicate the major tributaries and the corresponding tectonic units that affect the zircon age population in each stream (He et al., 2013a; 2014, and references therein).

Ages of monazite in sediments from several river basins such as Red River, Ma River, Ca River, Thu Bon River, Dong Nai River, Mekong River, etc., have been determined to understand the age of lithologic formations in their upstream regions (e.g. Nagy et al., 2001; Tran et al., 2003; Kazumi et al., 2010). These reports show not only the formation ages, but also the major tectonic periods and related magma-metamorphic activities (Tran and Vu, 2011).

Originating from the Ngok Ro summit at the altitude of 1,240 m, in the Ngoc Linh mountain range, northwest of the Kontum Massif, Ba River (also known as Da Rang River) runs along the eastern slope of the Truong Son mountain ranges through Kon Tum, Gia Lai and Phu Yen provinces before flowing into the East Sea from the Da Rang estuary, in eastern Tuy Hoa. Occupying a catchment area of about 13,000 km^2 Ba River basin is considered as a site for transport and storage of eroded products from the Kontum massif, either by natural causes or by tectonic activities (Fig. 1).

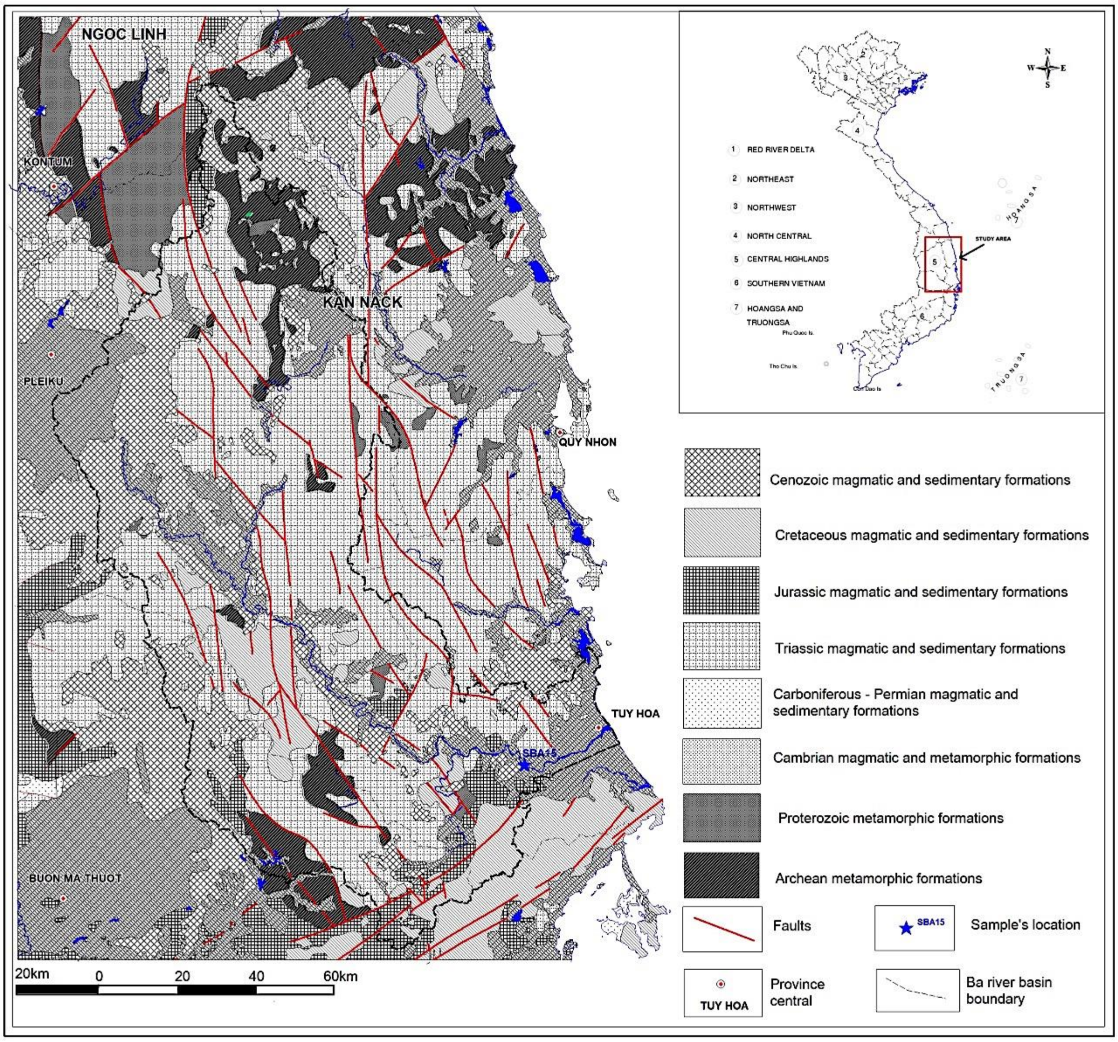


Figure 1. Simplified geological map and sampling site of Ba River basin

With the development of laser abrasion-attached inductively coupled plasma mass spectrometry technology (LA-ICP-MS), U-Pb isotopic analysis for a large amount of zircons ($ZrSiO_4$) to determine their crystalline ages have become easier, faster and reliable (Tran et al., 2003 and references therein). With purpose to decipher the formation (crystallization) ages of magmatic-metamorphic formations in the upstream of

Ba River, including the Kontum Massif, we have extracted and selected 122 zircon grains from representative sediment samples at a site in the downstream of Ba River to analyze for U-Pb- Th isotopic compositions by LA-ICP-MS method. The age data are processed and interpreted in the context of the relationship between the regional magma-metamorphic and thermo-tectonic events.

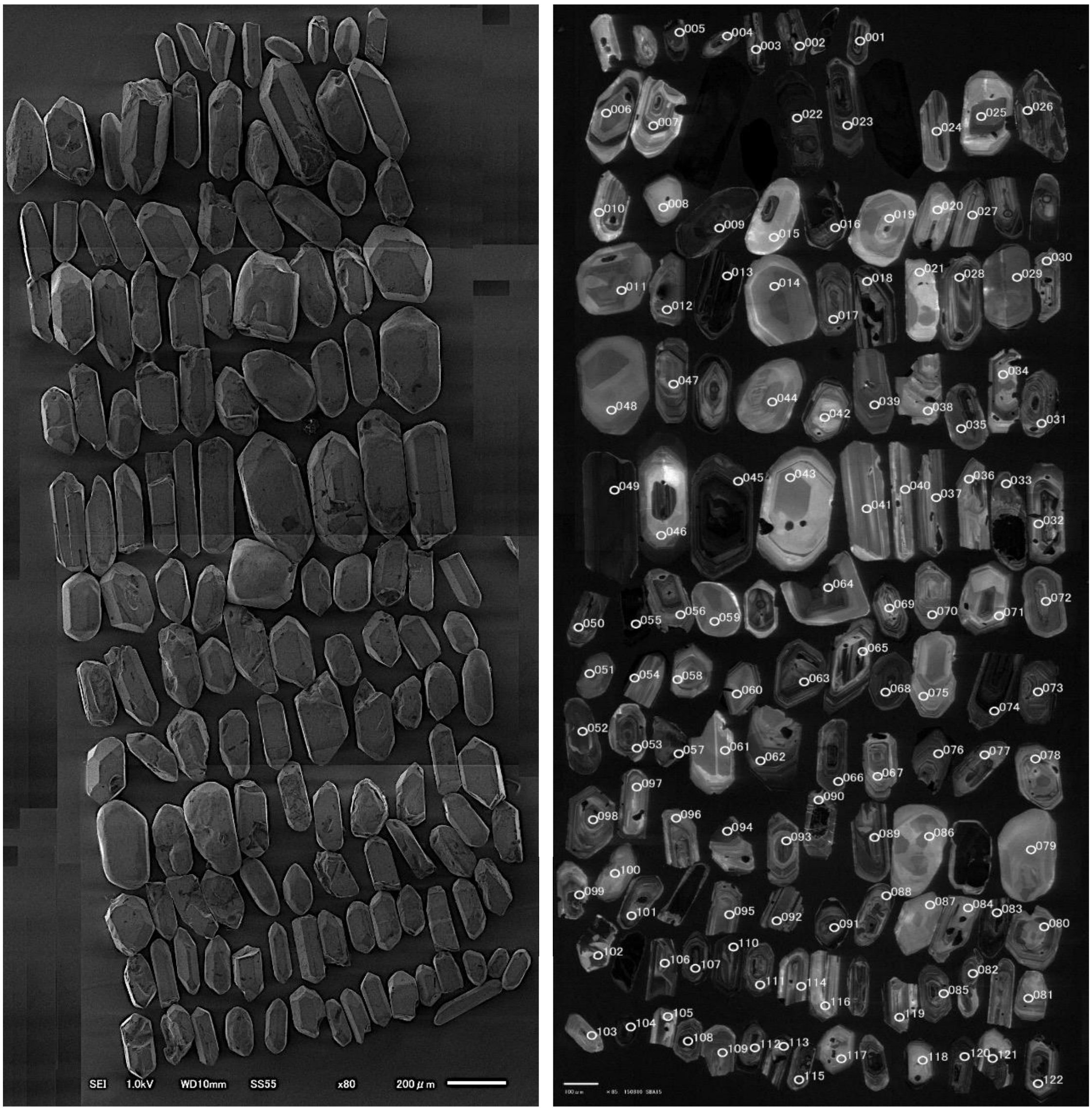
2. Sample collection, processing and analytical method

In order to guarantee the highest representativeness for the Ba River basin, single zircon crystals were separated and selected from a number of sediment samples weighed about 500 grams each, collected at sites in the Da Rang estuary, near Tuy Hoa city. The sample was coded as SBA 15 and illustrated in Fig. 1.

At the field, the samples were crushed to a size <2 mm, washed with running water several times to remove dusty (muddy) portions and to reduce the sample sizes. The samples were subsequently dried naturally. In the rock preparation laboratories, the sediment samples were crushed with jaw-crusher and sieved. Portions of ≤ 1 mm were washed in an ultrasonic bath in 500 ml Pyrex glass for about 30 minutes followed by multiple rinses with clean water to remove as much contaminant as possible. Ultrasonic washes and clean water rinses were repeated several times. The cleaned samples were then dried overnight in an oven at about 100°C. The zircon was divided by heavy liquid before using the Frantz magnetic separator to enrich the zircon grains following the method of Hutton (1950) and Mange and Maurer (1992). Thereafter, individual grains of zircon were handpicked under the microscope from heavy fractions that were kept separate from the sediment samples. The zircon grains, the zircon standard FC1 (Paces and Miller, 1993) and OT4 (Horie et al., 2013), and the glass standard NIST SRM610 were mounted in an epoxy resin (Fig. 2a). The zircon grains were polished till the center of the embedded grains exposed (Fig. 2b). Backscattered electron and cathodoluminescence images of zircon grains were taken using a SEM-CL equipment, JSM-6610 (JEOL) and cathodoluminescence detector (SANYU electron) at the National Museum of Nature and Science of Japan. The images were utilized to select spots for analysis. The U-Pb dating was performed using an LA-ICP-MS that was assembled by NWR213 (Electro Scientific Industries) and Agilent 7700x (Agilent Technologies) also at the National Museum of Nature and Science of Japan. Analytical procedures and measurement running conditions were described in Tsutsumi et al. (2012). The spot size of the laser was 25 μm. A correction for common Pb was done on the basis of the measured $^{208}Pb/^{206}Pb$ and Th/U ratios (^{208}Pb correction) (e.g. Williams, 1998) and the model for common Pb compositions proposed by Stacey and Kramers (1975).

3. Results

The results are presented in Table 1 and illustrated in Figs. 3-5. In 122 samples, 115 are concordant that form a concordia curve with $^{238}U/^{206}Pb$ (corrected) ranging from 0 to about 75 corresponding to $^{207}Pb/^{206}Pb$ (corrected) varying from 0.15 to 0.05 (Fig. 3). Generally, the data from four age groups, with group 1 ranging from 105 to 85 Ma (middle to late Cretaceous), group 2 from 270 to 211 Ma (e.g. middle Permian to Late Triassic), group 3 ranging between 455 and 424 Ma (late Ordovician to early Silurian), and group 4 scattering from 970 to 1470 (Mesoproterozoic). Particularly, one sample yields a value of 2383 ±24 Ma (Paleoproterozoic). As showed in Table 1 and Figs. 3 and 4 the majority of the age data concentrate on middle Permian (270 Ma)-Late Triassic (211 Ma) with 97 samples, accounting for 79,5% of samples analyzed.



(a) (b)

Figure 2. a- SEM images of unpolished zircons from SBA15;
b- SEM images of polished zircons from SBA15

Table 1. Some U-Pb zircon representative ages of SBA15 from Ba River basin

Labels	$^{206}Pb_c$ (1)	U	Th	Th/U	$^{238}U/^{206}Pb^*$ (1)		$^{207}Pb^*/^{206}Pb^*$ (1)		$^{238}U/^{206}Pb^*$ age (1)		$^{207}Pb^*/^{206}Pb^*$ age (1)		Disc (2)	Conc or disc
	(%)	(ppm)	(ppm)						(Ma)		(Ma)		(%)	
SBA15_001	0.95	467	201	0.44	25.16	±0.40	0.045	±0.0033	251.3	±3.9				Conc
SBA15_002	0.31	741	268	0.37	26.07	±0.34	0.0496	±0.0022	242.7	±3.1				Conc
SBA15_013	1.6	511	319	0.64	4.43	±0.05	0.0783	±0.0041	1312.2	±12.5	1155	±101	-13.6	Conc
SBA15_026	0.06	1609	116	0.07	14.26	±0.17	0.0562	±0.0010	437	±5.1				Conc
SBA15_040	0.28	86	115	1.38	74.74	±3.50	0.0444	±0.0213	85.7	±4.0				Conc
SBA15_091	0.57	827	424	0.53	2.5	±0.04	0.1532	±0.0022	2167.3	±28.5	2383	±24	9.1	Conc
SBA15_121	0.21	623	251	0.41	26.08	±0.48	0.0514	±0.0030	242.5	±4.3				Conc
SBA15_122	0.39	201	149	0.76	26	±0.67	0.0517	±0.0079	243.3	±6.2				Conc

Errors are 1-σ; Pbc and Pb* indicate the common and radiogenic portions, respectively.

(1) Common Pb corrected by assuming $^{206}Pb/^{238}U$-$^{208}Pb/^{232}Th$ age-concordance

(2) The degree of discordance for an analyzed spot indicates the chronological difference between the two ages determined by Pb–Pb and U–Pb methods, and is defined as $\{1-(^{238}U/^{206}Pb^*age)/(^{207}Pb^*/^{206}Pb^*\ age)\}\times100$ (%) (e.g., Biao et al., 1996).

Conc: Concordant; Disc: Discordant

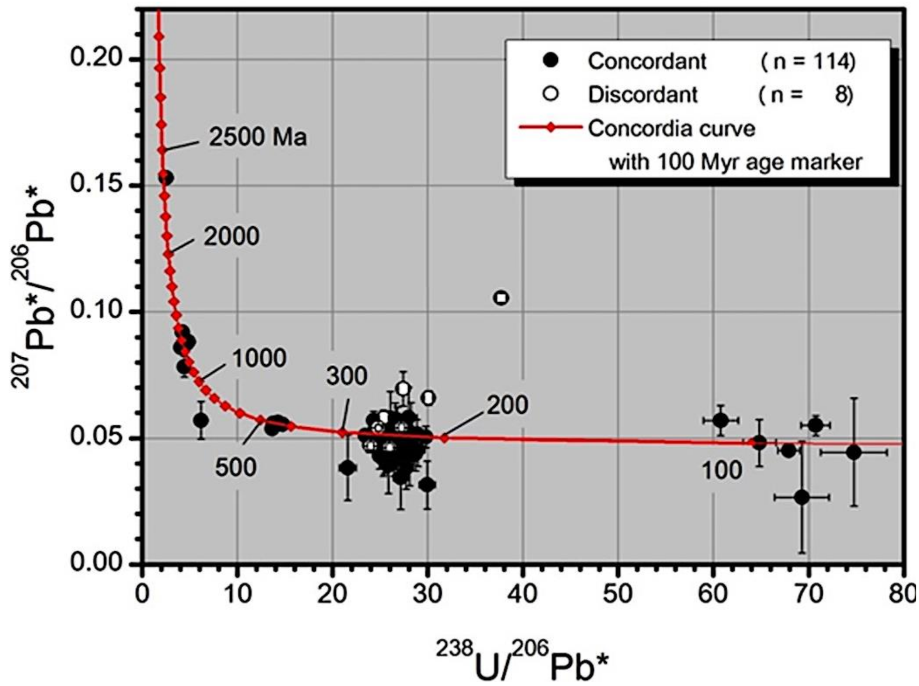


Figure 3. U–Pb zircons age concordia diagram for sample SBA15

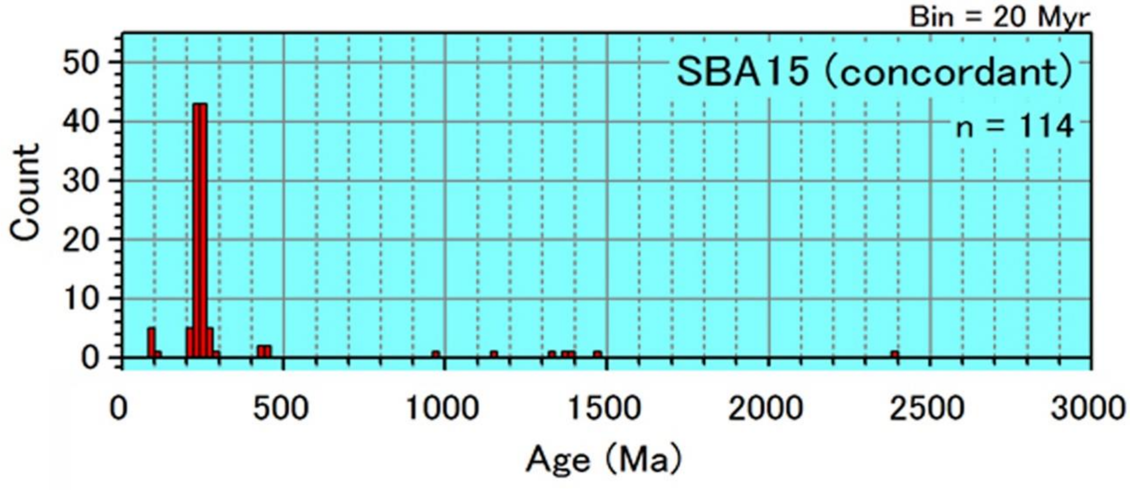


Figure 4. Distribution for U–Pb zircons age of sample SBA15

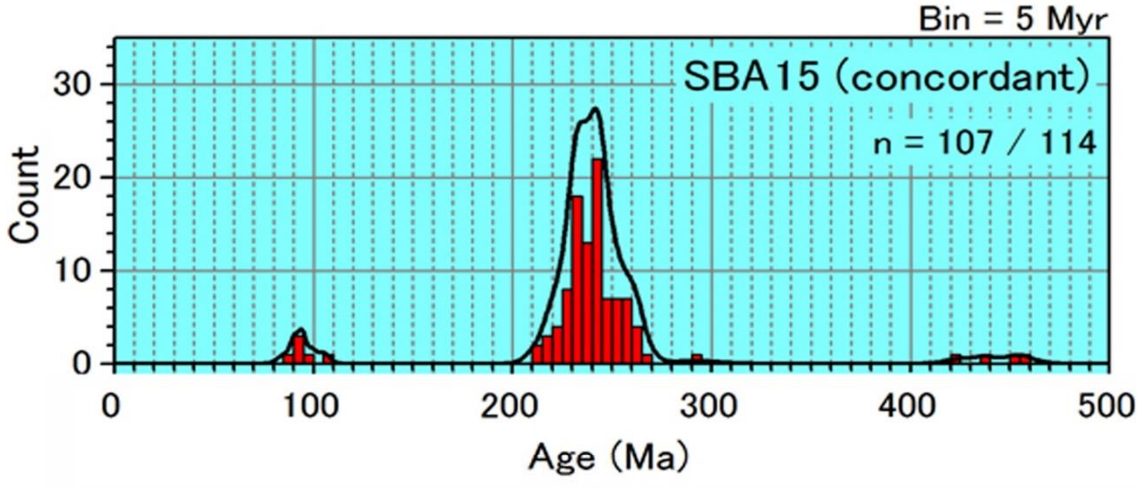


Figure 5. Distribution for the most significant of U–Pb zircons age of sample SBA15

4. Discussion

4.1. The tectonic stages of Kontum massif

Kontum massif comprises high-temperature and pressure metamorphic complexes such as amphibolite and granulite facies believed to be Paleoproterozoic (ca. 2500 Ma) (Phan C.T., 1989; Hutchison, 1989). These old metamorphic formations are partially overlain by Paleozoic-Mesozoic magma-sedimentary formations and/or Cenozoic basalts, and often penetrated by Triassic-Jurassic magmatic bodies (Fig. 1).

Structurally Kontum massif is controlled by 2 major fault systems: the north-south directed Poko fault in the west that extends to beneath Pleiku (Fig. 1), and the second system being east-west oriented Tra Bong-Phuoc Son fault zone, affecting much of the northern part of the massif (Lepvrier et al., 2004). These two fault zones are intersected in western Kontum massif, separating Kan Nack complex in the east from Ngoc Linh complex in the west, causing metamorphism to facies as high P-T as biotite-hornblende gneiss, amphibolite and granulite (Tran V.T., 1986;

Lepvrier et al., 2004; Vu V.T. et al., 2013). Isotopic ages determined for mineral assemblage in the metamorphic facies, except for the granulite, have yielded about 250 Ma (Vu V.T., 2004; Vu V.T. et al., 2013; Maluski et al., 2005).

Studies of crystalline ages of basement rocks in the Kontum massif suggested that the massif had undergone three metamorphic-tectonic stages. The oldest stage occurred about 1400 Ma according to the U-Pb isotopic ages acquired by SHRIMP method on zircons separated from a set of granulite (Tran N.N. et al., 2001). The second thermo- tectonic stage may have occurred during the period between 470 and 400 Ma, based on U-Pb and Ar-Ar isotopic ages, determined on minerals separated from amphibolite, granitogneiss, and granite migmatite etc. (Carter et al., 2001; Nagy et al., 2001; Nakano et al., 2003; Maluski et al., 2005; Nguyen T.D. et al., 2015). The third thermo-tectonic stage is believed to have occurred during the late Permian-late Triassic, which coincided with the time of Indosinian plate collision, convergence and orogeny (Lepvrier et al., 2004). Isotopic ages determined using different methods on minerals separated from granulite gneiss (pelitic granulite) yielded values of 254±12 Ma (Tran et al., 2001), 243±5, 248±6 and 256±6 Ma (Carter et al., 2001). On the other hand, U-Pb isotopic ages acquired on zircon separates from enderbite-charnockite gneiss associated with granulite in the Kan Nack complex showed similar values of 259.7±15.9 Ma (Tran, N.N. et al., 2002), 258±6 Ma (Carter et al., 2001), and 249±2 Ma (Nagy et al., 2001), mostly indicating late Permian-early Triassic. CHIME analysis conducted on single monazites from a gneiss sample containing a mineral assemblage of garnet (Grt)-orthopyroxene (Opx)-sillimanite (Sil)-quartz (Qtz) yielded an age of 248±16 Ma (Osanai et al., 2001).

A Sr-Nd isotopic study of (supposed) Archean and Proterozoic metamorphic rocks in the Indochina block by Lan et al. (2003) suggested that the gneiss and schist are of heterogeneous calc-alkaline in origin whereas the majority of amphibolites show geochemical characteristics of intraplate tholeiitic basalts. These authors explain that the gneiss and schist are formed from Proterozoic crustal rocks while the amphibolite is believed to originate from basalts occurred following the Paleozoic rifting that separated Indosinian block from Gondwana (Lan et al., 2003; see Hutchison, 1989; Carter et al., 2001; Nagy et al., 2001). During the convergence with other continental blocks in Southeast Asia in the Permian-Triassic period, the Indosinian Block had undergone orogeny marked by high temperature metamorphism to granulite facies in the deep core of the block in association with charnockite magmatism resulted in the exhumation of the region (Lepvrier et al., 1997; Tran et al., 2001; Carter et al., 2001; Lan et al., 2003; Vu et al., 2013).

4.2. The significance of U-Pb zircon ages of Ba River basin

The most prominent features of zircon include high hardness (7.5 in the Mohs scale), durability to surface processes and chemical inertia. Being very durable to thermal and abrasive processes, zircon remains virtually intact in sediment and becomes one of the major components of sand. With the above physio-chemical properties, U-Pb isotopic ages of zircon separate from Mesoarchean gneisses (3.2-2.8 Ga) from northern China craton by LA-ICP-MS can still provide very reliable results (Liu et al., 2017).

Zircon samples collected in the Ba River basin provided the following age groups (1) middle to late Cretaceous (105 to 85 Ma), (2) middle Permian to Late Triassic (270 to 211 Ma), (3) late Ordovician-early Silurian

(455 to 424 Ma), and (4) showing a set of ages scattering from 970 to 1470 Ma (Mesoproterozoic) and a sample dated at 2383±24 Ma. However, data predominantly fall in middle Permian-Late Triassic group (270-211 Ma) with 95 out of 122, accounting for 83% of the samples analyzed. As noted above, these age groups have been proven to exist and reflect the thermo-tectonic stages having occurred following the formation and development of the Kontum massif (Lan et al., 2003; Lepvrier et al., 2008; Vu et al., 2013). Tran N.N. (2004) reported U-Pb isotopic ages of zircons separated from an orthogneiss in the Re River complex, northern Kontum. Aside from the ages of about 436±10 Ma (the age group of 410-450 Ma in Nagy et al., 2001), the author also reported ages as old as 2540-2590 Ma. This Paleoproterozoic age was explained as evidence of ancient middle crust material having been brought to the surface by Ordovician-Silurian magmas (e.g. Nagy et al., 2001; Tran N.N., 2004). Paleoproterozoic formations have not been discovered. The age value of 2383±24 Ma identified in this report may also be an ancient crustal material brought to the surface by a Paleozoic magmatic event (Table 2).

Table 2. Statistics of U-Pb zircon ages of SBA15 from Ba river basin

Period	Total zircon grains	Age (Ma.)
Cretaceous- Jurassic	7	85.7÷168.7
Triassic	85	210.9÷251.3
Permian	19	251.5÷292
Silurian	4	424.2÷455.7
Proterozoic	7	969.2÷2383

5. Concluding remarks

Previous isotopic age groups reported for the metamorphic formations in the Kontum massif demonstrated that the massif had undergone three major tectonic stages during its development history. The oldest period occurred in the Mesoproterozoic (1600-1000Ma), the second phase may have occurred between the Early Ordovician and late Silurian (about 470-400 Ma), while the third stage may take place from the Middle Permian to Late Triassic (270 -210 Ma). The latter was viewed as an immense tectonic period as a result of collision between Indosinian block with other micro-continents in Southeastern Asia.

The isotopic ages acquired from zircons separated and selected from the representative sediment samples at the Ba River downstream include 3 major age associations of 1470-970Ma, 455-424 Ma, and 270-211 Ma, coinciding with age groups that reflect three major tectonic stages having occurred during the formation and evolution of the Kontum massif. The age coincidence, on the one hand, lends a firm support to the published isotopic ages for the magma-metamorphic formations in the Kontum massif, and suggests, on the other hand, that U-Pb isotopic ages acquired from zircons collected in the downstream area of a river basin may reflect ages of many lithologic formations in the upstream area.

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