U-Pb ages and Hf isotopic composition of zircon and bulk rock geochemistry of the Dai Loc granitoid complex in Kontum massif: Implications for early Paleozoic crustal evolution in Central Vietnam

Pham Trung HIEU*, Nguyen Thi DUNG**, Nguyen Thi Bich Thuy***, Nguyen Trung MINH** and Pham MINH*

*Faculty of Geology, University of Science VNU-HCM, Ho Chi Minh, Vietnam  
**Vietnam National Museum of Nature, Ha Noi, Vietnam  
***General Department of Geology and Minerals of Vietnam, Ha Noi, Vietnam

The northern Kontum massif in central Vietnam, one of the most key tectonic and metallogenic terranes of the Indochina block, consists of numerous volcano-plutonic complexes including the Dai Loc granite complex that formed an essential part of the early Paleozoic batholith of the massif. Rocks of the Dai Loc complex are granodiorite and granite in composition. Geochemically, the rocks are of sub-alkaline affinity and belong to high-potassium series. These rocks have moderate Aluminum Saturation Index (ASI) values of 0.76–1.19 and low Mg# values of 23–39. Zircon grains separated from the rocks have high εHf(t) values and old Hf model ages (TDM) which varying from −0.7 to +4.8 and 0.9 to 1.1 Ga, respectively. All these characteristics, in conjunction with trace element features, suggest generation by partial melting of crustal source rocks with additional input of mantle-derived material. Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) zircon U-Pb analytical results from two samples revealed emplacement ages of the granite at 423 ± 2.2 and 427 ± 9.9 Ma. Our geochronological data provide evidence for early Paleozoic crustal evolution in Central Vietnam.

Keywords: Kontum massif, Dai Loc granitoid, Zircon Hf isotopes, Early Paleozoic

INTRODUCTION

Southeast Asia is a collage of some allochthonous Gondwanaland-derived microplates (Leloup et al., 1995; Nam, 1998; Carter et al., 2001; Leloup et al., 2001; Hieu et al., 2012, 2013; Nguyen et al., 2014). Amalgamation processes of these microplates played an important role in the evolution of the eastern Tethyan belt as well as its surrounding regions and eventually result in the formation of the SE Asian continent during the Paleozoic and Mesozoic era (Metcalfe, 1988, 1990; Lepvrier et al., 2008; Nakano et al., 2013). The northern Kontum massif (also called as southern Truong Son terrane), located in central Vietnam, is one of the most key tectonic and metallogenic terranes in Indochina block. Together with the Truong Son terrane, the northern Kontum massif shapes the northeastern part of the Indochina terrane (Fig. 1a). Monazite U-Th-Pb ages gained from sixty samples of metamorphic and granitic rocks in the Kontum massif cluster around two age groups: Ordovician to Silurian and Late Permian to Early Triassic (Nakano et al., 2013). The dating results indicate that the best-known Precambrian basement of central Vietnam was experienced a high-grade metamorphism during both the Permian-Triassic and the Ordovician-Silurian. According to recent works (e.g., Tri and Khuc, 2009), numerous Ordovician-Silurian and Late Permian–Early Triassic granitoids are discovered in this area. The northern Kontum massif is made up of metamorphic rocks of the Tan Lam, Long Dai, A Vuong and Kham Duc Formations, and magmatic rocks of the Deo Ca, Ben Giang-Que Son, as well as the Dai Loc complexes (Fig. 1b).

The Dai Loc granitoid complex is a key part of the northern Kontum massif. So far, numerous mineralogical
and petrological studies were conducted on the Dai Loc complex by many Vietnamese and foreign geologists (e.g., Dovjikov, 1965; Thuc and Trung, 1995; Bao, 2000; Carter et al., 2001; Vuong et al., 2004; Nakano et al., 2013). Exact emplacement ages and geochemistry of the granitoids can provide a better understanding of the geodynamic processes as well as the tectonic evolution of central Vietnam and the Indochina terrane. Most previous studies reported emplacement ages for the Dai Loc granitoids are 310 Ma by K–Ar isochron (Thuc and Trung, 1995) and 418 Ma by U–Pb zircon method (Carter et al., 2001). This paper presents whole-rock geochemical data and U–Pb ages and Hf isotopic composition of zircons from the Dai Loc granitoid complex in efforts to assess its petrogenesis and to understand the crustal evolution of central Vietnam.

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

Geological setting

The Kontum massif, located in central Vietnam, hosts the largest outcrop of metamorphic rocks (Fig. 1). The basement of the massif consists of a basic geological unit of the Indochina terrane and was considered as its stable continental core (Hutchison, 1989). The major constituent of the Kontum massif is high-grade metamorphic rocks in Late Permian to Early Triassic (Osanai et al., 2001; Nagy et al., 2001; Nam et al., 2001, 2004a, 2004b; Nakano et al., 2004, Osanai et al., 2004; Owada et al., 2004; Osanai et al., 2005, 2006; Owada et al., 2006; Nakano et al., 2007, 2008). Precambrian sedimentary rocks have not been found in this massif.

The northern Kontum massif is bounded by the Song Ma suture in the north and the Tam Ky – Phuoc Son fault in the south (Fig. 1a). Paleozoic to Mesozoic intrusive granitoids are exposed widely in the massif [DGMVN (Department of Geology and Minerals of Vietnam), 1989, 1995; Nam 1998; Nam et al., 2001]. According to Hieu et al. (2015), granitoids in the northern Kontum massif can be divided mainly into four complexes based on zircon U–Pb ages and geochemical and Nd–Hf isotopic compositions, namely: the Hai Van, Ben Giang–Que Son, Deo Ca, and Dai Loc complexes (Fig. 1b). Granitoids from the Dai Loc complex in this region are exposed hundreds of square kilometers. Rocks are of biotite-bearing granodioritic gneiss, granitic gneiss with muscovite in the marginal part of plutons and migmatite.

Figure 1. (a) Distribution of NW–SE to NNW–SSE trending shear zones (modified after Lepvrier et al., 2004). (b) Geological map of the study area (modified after DGMVN, 1995 and Hieu et al., 2015). The localities of present samples are also shown in (b). Color version is available online from http://doi.org/10.2465/jmps.151229.
Sample description

The Dai Loc complex is made up of granodiorite, granite and some aplitic dykes. Most of rocks are medium to coarse grain and display gneissic texture. In this study, five granitic samples were taken from the Dai Loc complex and their locations are shown in Figure 1. The collected samples are strongly foliated (samples DLT01 and DLT04 in Figs. 2c and 2e) and weakly foliated rocks (sample DLT03 and DLT07 in Figs. 2d and 2f). Petrographically, the rocks are mainly medium- to coarse-grained granite displaying porphyritic textures with K-feldspar phenocrysts. (c) and (e) Rock-forming minerals of the first group are plagioclase, quartz, biotite, and minor muscovite. (d) and (f) The second group consists of plagioclase, microcline, and biotite with minor quartz (Pl, plagioclase; Ms, muscovite; Qz, quartz; Bt, biotite). Color version is available online from http://doi.org/10.2465/jmps.151229.

Samples selected for age dating cover both strong (DLT02) and weak (DLT07) foliation textures.

ANALYTICAL METHODS

Major and trace element analyses

A total of five granitic samples from the Dai Loc complex were selected for major and trace element analysis. Rocks were crushed in a jaw crusher and then powdered in an agate mill to a grain size of <200 mesh. Major elements were analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG CAS). For major element analyses, mixtures of whole rock powder (0.5 g) and Li2B4O7 + LiBO2 (5 g) were made into glass disks and analyzed by X-ray fluorescence spectroscopy (XRF) with an AXIOS Minerals spectrometer. The analytical uncertainties were generally within 0.1–1% (RSD). Total iron is reported as Fe2O3.

Abundances of trace elements and rare Earth elements (REE) were determined by an Agilent 7500A in-
ductively coupled plasma mass spectrometry (ICP-MS) at the University of Science and Technology of China in Hefei, using a mixture of HF–HNO₃. The samples were placed in Teflon bombs with a stainless steel jacket were heated for 48 h at 195 °C, followed by evaporation on a hot plate at 145 °C, and then re-dissolved with 2 mL of distilled HNO₃ and dried again, and further digested with 3 mL of 30% HNO₃ at 195 °C for 12 h in the electric oven. Dissolved samples were then diluted to 80 g with 2% HNO₃ prior to further analysis.

**U–Pb LA-ICP-MS zircon analyses**

U–Pb ages and U–Th–Pb concentration in zircons were analyzed by using laser ablation inductively coupled plasma spectrometry (LA-ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. Both detailed operating conditions and data reduction were similar to those described by Liu et al. (2008, 2010). Laser sampling was conducted by using a GeoLas 2005 coupled with an Agilent 7500a ICP-MS instrument. We used a laser spot size of 32 µm as well as a laser repetition of 6 Hz during analyses. Quantitative calibration for trace element analyses and U–Pb zircon dating was carried out by ICPMSDataCal (Liu et al., 2008, 2010). Zircon 91500 was used as external standard for U–Pb dating, and was analyzed twice for every 5 spots. U–Th–Pb isotopic ratios used for 91500 were from Wiedenbeck et al. (1995). Concordia diagrams and weighted mean calculations were made using Isoplot/Excel version 3 (Ludwig, 2003).

**Zircon Hf isotope analyses**

The Hafnium (Hf) isotopic composition of zircons was analyzed by the LA- Multiple collector (MC)-ICP-MS method, using both a Thermo Finnigan Neptune multicollector ICP-MS and a Geolas CQ 193 nm laser ablation system housed at IGG CAS. Analyses were performed with a spot size of 44 µm, a laser repetition rate of 10 Hz, and a laser energy density of 100mJ/pluse. Helium was used as carrier gas in order to transport the ablated aerosols from the ablation cell to the ICP-MS torch. Interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of interference-free ^{175}Lu, which uses the recommended ^{176}Lu/^^{172}Lu ratio of 0.02669 (DeBievre and Taylor, 1993) and the isobaric interference of ^{176}Yb on ^{176}Hf was corrected by using a recommended ^{176}Yb/^^{172}Yb ratio of 0.5886 (Chu et al., 2002). Zircon 91500 was used as the reference standard, and our analyses yielded mean ^{176}Hf/^^{177}Hf ratios of 0.2822952 ± 0.0000056 (n = 111, 2σ). Decay constant for ^{176}Lu of 1.865 × 10⁻¹¹ a⁻¹ was used (Scherer et al., 2001). Variation of initial ^{176}Hf/^^{177}Hf ratios, denoted as ε_Hf(t), is calculated in related to the chondritic reservoir with a ^{176}Hf/^^{177}Hf ratio of 0.282772 and ^{176}Lu/^^{177}Hf of 0.0332 (Blichert-Toft and Albarede, 1997).

**ANALYTICAL RESULTS**

**Major and trace element geochemistry**

Major and trace element contents of five whole-rock samples from the Dai Loc complex are listed in Table 1. The rocks are characterized by high contents of SiO₂ (70.65–72.38 wt%) and total alkaline (Na₂O + K₂O = 7.33–9.23 wt%) with K₂O/Na₂O ratios >1,0 excluding of the sample DLT04 (K₂O/Na₂O = 0.96). In term of normative mineralogy, the analyzed samples have granitic composition and belong to high-K calc-alkaline series (Figs. 3a and 3b). All analyzed samples, except for sample DLT01, have the ASI values lower than 1.1 and contain nearly no muscovite. These characteristics indicate I-type granite for those samples. The sample DLT01 has ASI >1.1 and contains some muscovite, which meet criteria of S-type granite (Chappell and White, 1974). However, the muscovite in this sample is not a primary, but secondary mineral forming by replacement of biotite during metamorphism or deformation took place after emplacement of granite, perhaps during Late Permian–Early Triassic (Nakano et al., 2013). The chondrite-normalized REE patterns of all analyzed samples are characterized by mormerate fractionation between the light and heavy REEs [(La/Yb)n = 8.8–13.8] and negative Eu anomalies (Eu/Eu* = 0.40–0.68) (Fig. 4a). The N-MORB-normalized spidergram show enrichment in large ion lithophile (LIL) elements (e.g., Cs, Rb, Pb, and K) and exhibit distinct negative anomalies for some high field strength (HFS) elements (Nb and Ti) (Fig. 4b).

**Zircon U–Pb ages**

Two samples (DLT02 and DLT07) from the Dai Loc granitoids were subjected to single-zircon U–Pb dating (Table 2). Zircon grains extracted from sample DLT02 are mostly colorless, transparent and show clear oscillatory zoning (Fig. 5) with Th/U ratios of 0.19 to 0.90, indicating magmatic origin (Corfu et al., 2003). Nineteen grains have been analysed for U–Pb isotopic composition. Of which sixteen grains yield concordant U–Pb ages around 427 Ma, defining a weighted mean ²⁰⁶Pb/²³⁸U age of 426.9 ± 9.9 Ma (n =16, MSWD =0.42; Fig. 6a).
Ma is considered as the crystallization age of this sample. Other three zircon grains yield much older U–Pb ages ranging from Neoproterozoic (976–588 Ma) to Early Cambrian (523 Ma). These ages reflect the inherited zircon cores that provide evidence for older pre-existing crustal sources from which the magma was derived (e.g., Hoskin and Schaltegger, 2003).

Sample DLT07 consists of prismatic and elongated or stubby zircons, having lengths and length/width ratios ranging from 120 to 300 µm, and 1:1 to 1:3, respectively (Fig. 5). All Th/U ratios of these zircons (0.36–1.15) are higher than 0.1 and CL images display oscillatory zoning in all grains. Twenty zircon grains of this sample were analyzed for their U–Pb isotopic composition. All analyzed grains, excludes one grain giving Neoproterozoic 206Pb/238U age of 595 Ma, yield nearly concordant U–Pb ages around 423 Ma, with a weighted mean 206Pb/238U age value of 423 ± 2 Ma (n = 19, MSWD = 1.12; Fig. 6b). The age of 423 Ma is interpreted as the best estimate of the emplacement age of this sample.

Hf isotopic composition

Zircon grains from one sample (DLT 02) were analyzed on the same zircon spots when U–Pb dating had been performed. Nineteen analytical spots were located on ten zircon grains of the sample. The 176Hf/177Hf ratios vary from 0.282513 to 0.282686 and the 176Lu/177Hf ratios range from 0.001733 to 0.005194. An age of 427 Ma from sample DLTD02 of this study was used to calculate initial Hf isotope composition. The zircons of granite exhibit relative uniform (176Hf/177Hf)i values of from 0.282511 to 0.282679, corresponding to εHf (t) values from −0.7 to +4.8 (Table 3). Depleted mantle model ages (TDM) are in the range of 903–1102 Ma (Table 3).

DISCUSSION

Petrogenesis of the Dai Loc granite

The Dai Loc granites are characterized by relatively high SiO2 (70.65–72.89 wt%), Al2O3 (13.83–14.87 wt%) and low TiO2 (0.30–0.54 wt%), MgO (0.51–1.12 wt%), and CaO (0.29–3.26 wt%) contents. Analyzed samples belong to the high-K, calc-alkaline magma series with moderate aluminum saturation indices (around 1.0) and contain no primary muscovite indicating affinity of I-type granite. The granites are further characterized by relative low Mg# of 31–36 and TDM model ages range from 896 to 1102 Ma suggesting generation by partial melting of juvenile mafic crustal source rock. This is supported by high εHf values varying from −0.7 to +4.8 (most εHf values > +1.5). The Dai Loc granites are high-K, calc alkaline rocks and enriched in LILEs such as Cs, K, Rb, U, and Th with respect to the HFSEs, especially Nb and Ti (Fig.
4). Magmas with these chemical features are generally believed to be generated in subduction-related environments or their protolith was produced in a subduction context (e.g., Rogers and Hawkesworth, 1989; Sajona et al., 1996). Many studies suggest that trace elements could be used as discriminatory tools to distinguish among different tectonic settings of granitoid magmas. Pearce et al. (1984) used the Rb, Y, and Nb elements as the most efficient discriminants amongst ocean-ridge granites (ORG), within-plate granites (WPG), volcanic-arc granites (VAG) and syn-collisional granites (syn-COLG). Applying their discrimination criteria, the Dai Loc granites are classified as VAG (Figs. 4c and 4d). Nakano et al. (2013) also pointed out the presence of the Ordovician–Silurian volcanic arc magmatism in the Truong Son Belt obtained by U–Pb zircon and whole rock geochemistry from granitic gneiss collected in the Kontum massif. Reworking of crustal rocks to form the Dai Loc granitoids perhaps took place during Ordovician–Silurian times which corresponding to the first thermal episode of Nakano et al. (2013). The crustal source rocks are probably less Mesozoic and Neoproterozoic in age as revealed by inherited U–Pb zircon (976 Ma) and TDM (896–1102 Ma). This is totally compatible with suggestion of Lan et al (2003) that the Neoproterozoic event is the magmatism for the formation of the protolith of Dai Loc complex in central Vietnam and the granodiorite of East Coast Province of Peninsular Malaysia.

Crystallization age of the granite

Zircon crystals separated from two granitic samples have almost the same characteristics. Most of them are prismatic in shape and display oscillatory zoning (Fig. 5).
To constrain the crystallization age of the granitic rocks, we conducted LA-ICP-MS U-Pb analyses for distinct oscillatory zoning parts. Total 39 data points from samples DLT02 and DLT07, of which 35 analytical points plot on or nearly on the concordant curves which yield average $^{206}\text{Pb}/^{238}\text{U}$ age values of 426.9 ± 9.9 and 423 ± 2.2 Ma, respectively (Figs. 6a and 6b). The consistent ages obtained by U-Pb isotopes, together with internal structures of zircon revealed by CL images, allow us to conclude that crystallization of the Dai Loc granite took place during Mid Silurian at 427–423 Ma. This age is consistent with the conclusions from the previous researchers preceding Ordovician–Silurian age in the Kontum massif (Carter, et al., 2001; Nagy et al., 2001; Vuong et al., 2004, Nakano et al., 2013), in northeastern Vietnam (Nguyen et al., 2014) and in South of China (e.g., Li, 2011). Other four zircon grains yield Neoproterozoic (976–588 Ma) to Early Cambrian (523 Ma) age. These indicate the presence of inherited zircon core and provide evidence for older pre-existing crustal sources from which the magma was derived (e.g., Hoskin and Schaltegger, 2003).

### Table 2. Zircon U-Pb analytical data of the Dai Loc granitoid

| Sample  | Th/U | $^{206}\text{Pb}/^{206}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{208}\text{Pb}/^{238}\text{U}$ | $^{235}\text{U}/^{238}\text{U}$ | $^{207}\text{Pb}/^{206}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{238}\text{U}$ | $^{208}\text{Pb}/^{235}\text{U}$ | $^{208}\text{Pb}/^{238}\text{U}$ | $^{208}\text{Pb}/^{235}\text{U}$ | $^{208}\text{Pb}/^{238}\text{U}$ |
|---------|------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| DLT02   | -1   | 0.45 0.06003 0.00447 0.55037 0.04874 0.06636 0.00342 445.32 414.21 107 | -2   | 0.82 0.05688 0.00428 0.52365 0.04694 0.06634 0.00343 428.31 414.21 103 | -3   | 0.62 0.05858 0.00471 0.56196 0.05254 0.07018 0.00363 453.34 437.22 104 | -4   | 0.69 0.05437 0.00417 0.51299 0.04575 0.06805 0.00345 420.31 424.21 99 | -5   | 0.83 0.08034 0.00629 0.70554 0.06360 0.06333 0.00322 442.38 396.20 137 | -6   | 0.29 0.05585 0.00422 0.50901 0.04428 0.06581 0.00321 418.30 411.20 102 | -7   | 0.63 0.05817 0.00473 0.57200 0.05232 0.07178 0.00359 459.34 447.22 103 | -8   | 0.53 0.05790 0.00446 0.54399 0.04753 0.06800 0.00334 441.31 424.20 104 | -9   | 0.33 0.05517 0.00424 0.51923 0.04505 0.06807 0.00331 425.30 424.20 100 | -10  | 0.64 0.05872 0.00464 0.54458 0.04787 0.06725 0.00328 441.31 420.20 105 | -11  | 0.52 0.05349 0.00424 0.50336 0.04421 0.06828 0.00328 414.30 426.20 97 | -12  | 0.19 0.05929 0.00480 0.78463 0.06948 0.09585 0.00459 588.40 590.27 100 | -13  | 0.53 0.05180 0.00432 0.51193 0.04628 0.07163 0.00341 420.31 446.21 94 | -14  | 0.61 0.06882 0.00544 0.62328 0.05343 0.06566 0.00310 492.33 419.10 120 | -15  | 0.44 0.05121 0.00412 0.50599 0.04406 0.07224 0.00339 416.30 450.20 92 | -16  | 0.90 0.07059 0.00585 0.67439 0.05928 0.06903 0.00322 523.36 430.19 122 | -17  | 0.60 0.05531 0.00436 0.50898 0.04294 0.06694 0.00307 418.29 418.19 100 | -18  | 0.50 0.06928 0.00690 1.61411 0.15520 0.16759 0.00809 976.60 999.45 98 | -19  | 0.67 0.06371 0.00524 0.61902 0.05342 0.07084 0.00322 489.34 441.19 111 | -20  | 0.37 0.05570 0.00135 0.53683 0.01285 0.06990 0.00087 436.8 436.5 100 |

Conc.% = $\left(\frac{^{206}\text{Pb}}{^{238}\text{U}}\right)\times\left(\frac{^{207}\text{Pb}}{^{235}\text{U}}\right)\times100$. 

To constrain the crystallization age of the granitic rocks, we conducted LA-ICP-MS U-Pb analyses for distinct oscillatory zoning parts. Total 39 data points from samples DLT02 and DLT07, of which 35 analytical points plot on or nearly on the concordant curves which yield average $^{206}\text{Pb}/^{238}\text{U}$ age values of 426.9 ± 9.9 and 423 ± 2.2 Ma, respectively (Figs. 6a and 6b). The consistent ages obtained by U-Pb isotopes, together with internal structures of zircon revealed by CL images, allow us to conclude that crystallization of the Dai Loc granite took place during Mid Silurian at 427–423 Ma. This age is consistent with the conclusions from the previous researchers preceding Ordovician–Silurian age in the Kontum massif (Carter, et al., 2001; Nagy et al., 2001; Vuong et al., 2004, Nakano et al., 2013), in northeastern Vietnam (Nguyen et al., 2014) and in South of China (e.g., Li, 2011). Other four zircon grains yield Neoproterozoic (976–588 Ma) to Early Cambrian (523 Ma) age. These indicate the presence of inherited zircon core and provide evidence for older pre-existing crustal sources from which the magma was derived (e.g., Hoskin and Schaltegger, 2003). Alternatively, Neoproterozoic crusts were
important sources for the Dai Loc complex in particular and for the Phanerozoic rocks in general (Lan et al., 2003).

**Implications for early Paleozoic tectonic evolution in Central Vietnam**

Single zircon U-Pb ages for the Dai Loc granites in this study, in combination with the previous published geochronological data, point to early Paleozoic magmatism in the study area which produced the 427–423 Ma Dai Loc granites. Such age is comparable to the inferred ages of many granites in southeast Asia. Early Paleozoic magmatism has been also identified in northeast Vietnam (Nguyen et al., 2014), in eastern Tibet, western Yunnan and in the Cathaysia Block (e.g., Li, 2011). An early Paleozoic event also was identified by SHRIMP U-Pb zircon concordia ages of gneisses in Kontum massifs (407 ± 11 to 444 ± 17 Ma; Carter et al., 2001) and U-Pb zircon concordia ages of a granodiorite of Kontum massif (451 ± 3 Ma; Nagy et al., 2001). In addition, inherited zircon ages, together with depleted mantle model ages (TDM) obtained from zircon Hafnium isotopes indicated a crustal formation event during Neoproterozoic time in the study area. Zircon U-Pb age and geochemical characteristics of the Dai Loc granites from our study suggest the presence of subduction-related magmatism in the region. This is coincide with conclusion of Nakano.
et al (2013) that in the Ordovician–Silurian, the region was characterized by active continental margin tectonics, followed by continental collision during the Late Permian to Early Triassic and subsequent exhumation during the Late Triassic (Hieu et al., 2015).

CONCLUSION

The Dai Loc granites in northern Kontum massif are of sub–alkaline affinity and belong to high K–calc alkaline series. The rocks display features of I-type granite. Geochemical and Hafnium isotope characteristics suggest that the Dai Loc granites were generated by partial melting of juvenile mafic crusts, which are probably Neoproterozoic in age as identified by inherited zircon age and depleted mantle model (TDM) ages.

The LA-ICP-MS zircon U–Pb dating provides the crystallization age of the Dai Loc granites of ~ 430 Ma. This age, together with previous reported in the region, points to the existence of the Early Paleozoic magmatism in this study area.

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SUPPLEMENTARY MATERIALS

Color version of Figures 1–4 is available online from http://doi.org/10.2465/jmps.151229.

REFERENCES

Bao, N.X. (2000) Tectonics and metallogeny of southern Vietnam. Project Report, South Vietnam Geological Mapping Division, Ho Chi Minh (in Vietnamese).
Blichert-Toft, J. and Albarede, F. (1997) The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle–crust system. Earth and Planetary Science Letters, 148, 243–258.
Carter, A., Roques, D., Bristow, C. and Kinny, P. (2001) Understanding Mesozoic accretion in Southeast Asia: significance of Triassic thermotectonism (Indosinian orogeny) in Vietnam. Geology, 29, 211–214.
Chappell, B.W. and White, A.J.R. (1974) Two contrasting granite types. Pacific Geology, 8, 173–174.
Chu, N.-C., Taylor, R.N., Chavagnac, V., Nesbitt, R.W., Boella, R.M., Milton, J.A., German, C., Bayon, G. and Burton, M. (2002) Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. Journal of Analytical Atomic Spectrometry, 17, 1567–1574.
Corfu, F., Hanchar, J.M., Hoskin, P.W.O. and Kinny, P. (2003) Atlas of zircon textures. In Zircon. (Hanchar, H.M. and Hoskin, P.W.O. Eds.). Reviews in Mineralogy and Geochemistry, 53, Mineralogical Society of America, Chantilly, VA, 469–500.
DeBievre, P. and Taylor, P.D.P. (1993) Table of the isotopic composition of the elements. International Journal of Mass Spec-

Table 3. Zircon Hf isotopic composition of the Dai Loc granitoid

| Sample | 176Yb/177Hf | 176Lu/177Hf | 176Hf/177Hf | ±2σ 176Hf/177Hf(f) | εHf(t) | ±2σ | TDM(Ma) |
|--------|-------------|-------------|-------------|-------------------|-------|-----|---------|
| DLT02  |             |             |             |                   |       |     |         |
| -01    | 0.159674    | 0.0038996   | 0.282644    | 17 0.282642       | 3.7   | 0.6 | 936     |
| -02    | 0.1428014   | 0.0035233   | 0.282629    | 14 0.282627       | 3.2   | 0.5 | 949     |
| -03    | 0.0726195   | 0.001733    | 0.282567    | 15 0.282565       | 1.6   | 0.5 | 992     |
| -04    | 0.0981859   | 0.0023945   | 0.282684    | 13 0.282598       | 2.5   | 0.5 | 962     |
| -05    | 0.1023956   | 0.0023563   | 0.28255     | 12 0.282548       | 0.8   | 0.4 | 1035    |
| -06    | 0.1009826   | 0.0025046   | 0.282603    | 17 0.282601       | 2.6   | 0.6 | 960     |
| -07    | 0.0903024   | 0.0023398   | 0.282573    | 16 0.282571       | 1.6   | 0.6 | 1000    |
| -08    | 0.1409393   | 0.0035387   | 0.282617    | 18 0.282615       | 2.8   | 0.6 | 968     |
| -09    | 0.1158635   | 0.0029471   | 0.282612    | 19 0.282610       | 2.8   | 0.7 | 960     |
| -10    | 0.0761428   | 0.0017479   | 0.282515    | 11 0.282513       | -0.3  | 0.4 | 1068    |
| -11    | 0.2221218   | 0.0051937   | 0.282678    | 17 0.282675       | 4.5   | 0.6 | 920     |
| -12    | 0.1119435   | 0.0027119   | 0.282586    | 13 0.282584       | 2.0   | 0.5 | 991     |
| -13    | 0.1121447   | 0.002821    | 0.282571    | 18 0.282569       | 1.4   | 0.6 | 1017    |
| -14    | 0.149744    | 0.0036763   | 0.28264     | 15 0.282638       | 3.6   | 0.5 | 937     |
| -16    | 0.1089368   | 0.0028086   | 0.282513    | 21 0.282511       | -0.7  | 0.7 | 1107    |
| -17    | 0.1020217   | 0.0023724   | 0.282582    | 11 0.282580       | 1.9   | 0.4 | 988     |
| -18    | 0.1796364   | 0.0045505   | 0.282681    | 15 0.282679       | 4.8   | 0.5 | 996     |
| -19    | 0.2077034   | 0.0050411   | 0.282686    | 17 0.282684       | 4.8   | 0.6 | 903     |

t, 427 Ma for sample DLT02.
Zircon U-Pb ages and Hf isotopic composition of Dai Loc granitoid

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trometry and Ion Processes, 123, 149–166.

DGMVN (Department of Geology and Minerals of Vietnam) (1989) Geology of Vietnam. Science Publisher, Hanoi, 1, 1–378 (in Vietnamese).

DGMVN (Department of Geology and Minerals of Vietnam) (1995) Geology of Vietnam. Science Publisher, Hanoi, 1, 1–359 (in Vietnamese).

Dovjikov, A.E. (1965) Geology of Northern Vietnam. Technical and Scientific Publisher, Hanoi (in Vietnamese).

Hieu, P.T., Chen, F., Thuy, N.T.B., Cuong, N.Q. and Li, S. (2015) Late Permian to Early Triassic crustal evolution in northwestern Vietnam. Journal of Geodynamics, 69, 106–121.

Hieu, P.T., Yang, Y.-Z., Do, Q.B., Nguyen, T.B.T., Le, D.P. and Chen, F. (2015) Late Permian to Early Triassic crustal evolution of the Kontum massif, central Vietnam: zircon U-Pb ages and chemical and Nd-Hf isotopic composition of the Hai Van granitoid complex. International Geology Review, 57, 1877–1883.

Hoskin, P.W.O. and Schaltegger, U. (2003) The composition of zircon and igneous and metamorphic petrogenesis. Reviews in Mineralogy and Geochemistry, 53, 27–62.

Hutchinson, C.S. (1989) Geological evolution of South-east Asia (Oxford Monographs on Geology and Geophysics). Oxford University Press.

Lan, C.Y., Chung, S.L., Long, T.V. and Lo, C.H. (2003) Geochemical and Sr-Nd isotopic constraints from the Kontum massif, central Vietnam on the crustal evolution of the Indochina block. Precambrian Research, 22, 7–27.

Leloup, P.H., Lacassin, R., Tapponnier, P., Schärer, U., Zhong, D.-L., Liu, X.-H., Zhang, S., Ji, S.-C. and Trinh, P.T. (1995) The Ailao Shan – Red river shear zone (Yunnan, China): Tertiary transform boundary of Indochina. Tectonophysics, 251, 3–84.

Leloup, P.H., Arnaud, N., Lacassin, R., Kienast, J.R., Harrison, T.M., Phan, T.T., Replumaz, A. and Tapponnier, P. (2001) New constraints on the structure, thermochronology and timing of the Ailao Shan Red River shear zone, SE Asia. Journal of Geophysical Research, 106, 6683–6732.

Lepvrier, C., Maluski, H., Yu, V.T., Leyreloup, A., Phan, T.T. and Nguyen, V.V. (2004) The early Triassic Indosinian orogeny in Vietnam (Truong Son Belt and Kontum massif): implications for the geodynamic evolution of Indochina. Tectonophysics, 393, 87–118.

Lepvrier, C., Vuong, N.V., Maluski, H., Thi, P.T. and Vu, V.T. (2008) Indosinian tectonics in Vietnam. Comptes Rendus Geoscience, 340, 94–111.

Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Wölley, A.R. and Zanetti, B. (1989) A classification of igneous rocks and glossary of terms. pp. 193, Blackwell, Oxford.

Li, L.-M. (2011) The crustal evolutionary history of the Cathaysian Block from the Paleoproterozoic to Mesozoic. pp. 210, Ph. D thesis, University of Hong Kong.

Liu, Y.-S., Hu, Z.-C., Gao, S., Günther, D., Xu, J., Gao, C.-G. and Chen, H.-H. (2008) In situ analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. Chemical Geology, 257, 34–43.

Liu, Y.-S., Gao, S., Hu, Z.-C., Gao, C.-G., Zong, K. and Wang, D. (2010) Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen: U-Pb dating, Hf isotopes and trace elements in zircons of mantle xenoliths. Journal of Petrology, 51, 537–571.

Ludwig, K.R. (2003) User’s manual for Isoplot 3.0: A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, Special Publication, 4, 1–71.

Metcalfe, I. (1988) Origin and assembly of Southeast Asia continental terranes. In Gondwana and Tethys (Audley-Charles, M.G. and Hallam, A. Eds.). Geological Society of London Special Publication, 37, 101–118.

Metcalfe, I. (1990) Allochthonous terrane processes in Southeast Asia. Philosophical Transactions of the Royal Society of London (Part A), 331, 625–640.

Nagy, E.A., Maluski, H., Lepvrier, C., Schärer, U., Phan, T.T., Leyreloup, A. and Vu, V.T. (2001) Geodynamic significance of the Kontum massif in central Vietnam: composite 40Ar/39Ar and U-Pb ages from Paleozoic to Triassic. Journal of Geology, 109, 755–770.

Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Tsunogae, T., Toyoshima, T. and Binh, P. (2004) Decompression process of mafic granulite from eclogite to granulite facies under ultra-high-temperature condition in the Kontum massif, central Vietnam. Journal of Mineralogy and Petrological Sciences, 99, 242–256.

Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Toyoshima, T., Binh, P., Tsunogae, T. and Kagami, H. (2007) Geologic and metamorphic evolution of the basement complexes in the Kontum massif, central Vietnam. Gondwana Research, 12, 438–453.

Nakano, N., Osanai, Y., Nguyen, T.M., Miyamoto, T., Hayasaka, Y. and Owada, M. (2008) Discovery of high-pressure granulite-facies metamorphism in northern Vietnam: Constraints on the Permo-Triassic Indochinese continental collision tectonics. Compites Rindus Geoscience, 304, 127–138.

Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Charusiri, P. and Khamphavong, K. (2013) Tectonic evolution of high-grade metamorphic terranes in central Vietnam: constraints from large-scale monazite geochronology. Journal of Asian Earth Sciences, 73, 520–539.

Nam, T.N. (1998) Thermotectonic events from Early Proterozoic to Mesozoic in the Indochina craton: implication of K-Ar ages in Vietnam. Journal of Asian Earth Sciences, 16, 475–484.

Nam, T.N., Sano, Y., Terada, K., Toriumi, M., Quynh, P.V. and Dung, L.T. (2001) First Shrimp U-Pb zircon dating of granulites from the Kontum massif (Vietnam) and tectonothermal implications. Journal of Asian Earth Sciences, 19, 77–84.

Nam, T.N., Osanai, Y. and Nakano, N. (2004a) Tectono-metamorphic evolution of crystalline basement complexes in the Kontum Massif, Vietnam: fact and question? Gondwana Research, 7, 1353–1355.

Nam, T.N., Osanai, Y., Nakano, N. and Tham, H.H. (2004b) Permo-Triassic ultrahigh-temperature metamorphism and continental collision in the Kon Tum massif. Journal of Geology, 285, 1–8 (in Vietnam with English abstract).

Nguyen, T.T.B., Hieu, P.T., Hai, T.T., Anh, B.T., Xuan, N.T. and Cung, D.M. (2010) Petrogenesis and zircon ages of the Thien Ke granitic in the Tam Dao region: Implications for early Paleozoic tectonic evolution in NE Vietnam. Journal of Minera-
Osanai, Y., Owada, M., Tsunogae, T., Toyoshima, T., Hokada, T., Trinh, V.L., Sajeev, K. and Nakano, N. (2001) Ultrahigh-temperature pelitic granulites from the Kontum massif, central Vietnam: Evidence for East Asian juxtaposition at ca. 250 Ma. Gondwana Research, 4, 720–723.

Osanai, Y., Nakano, N., Owada, M., Nam, T.N., Toyoshima, T., Tsunogae, T. and Pham, B. (2004) Permo-Triassic ultrahigh-temperature metamorphism in the Kontum massif, central Vietnam. Journal of Mineralogical and Petrological Sciences, 99, 224–241.

Osanai, Y., Nakano, N., Owada, M., Nam, T.N., Toyoshima, T. and Miyamoto, T. (2005) Tectonic evolution of the Kontum Massif in Vietnam and related Indochina regions. Earth Monthly, 27, 729–734.

Osanai, Y., Owada, M., Kamei, A., Hamamoto, T., Kagami, H., Toyoshima, T., Nakano, N. and Nam, T.N. (2006) The Higo metamorphic complex in Kyushu, Japan as the fragment of Permo-Triassic metamorphic complexes in East Asia. Gondwana Research, 9, 152–166.

Owada, M., Osanai, Y., Nakano, N., Nam, T.N., Binh, P., Matsuoka, T., Tsunogae, T., Toyoshima, T. and Kagami, H. (2004) Petrogenesis of the Late Permian Plei Man Ko granite in the Kontum massif, central Vietnam. Gondwana Research, 7, 1363–1365.

Owada, M., Osanai, Y., Hokada, T. and Nakano, N. (2006) Timing of metamorphism and formation of garnet granite in the Kontum Massif, central Vietnam: Evidence from monazite EMP dating. Journal of Mineralogical and Petrological Sciences, 101, 324–328.

Pearce, J.A., Harris, N.B. and Tindle, A.G. (1984) Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, 25, 956–983.

Pecceiello, A. and Taylor, S.R. (1976) Geochemistry of Eocene calc-alkaline volcanic rocks in the Kastamonu area, Northern Turkey. Contributions to Mineralogy and Petrology, 58, 63–81.

Rogers, G. and Hawkesworth, C.J. (1989) A geochemical traverse across the North Chilean Andes: evidence for crust generation from the mantle wedge. Earth and Planetary Science Letters, 91, 271–285.

Sajona, F.G., Maury, R.C., Bellon, H., Cotton, J. and Defant, M. (1996) High field strength elements of Pliocene-Pleistocene island-arc basalts Zamboanga Peninsula, Western Mindanao (Philippines). Journal of Petrology, 37, 693–726.

Schumer, E., Muenker, C. and Mezger, K. (2001) Calibration of the lutetium-hafnium clock. Science, 293, 683–687.

Sun, S.-S. and McDonough, W.F. (1989) Chemical and isotopic systematics of oceanic basalts implications for mantle composition and process. In Magmatism in the ocean basins (Saunders, A.D. and Nony, M.J. Eds.). Geological Society Special Publication, 42, 313–354.

Thuc, D.D. and Trung, H. (1995) Vietnam geology, part of II: magmat. Department of Geology and Mineral Resources Survey. Hanoi, 213–219 (in Vietnamese with English abstract).

Tri, T.V. and Khuc, V. (2009) Geology and earth resources of Viet- nam. Publishing House for Science and Technology, 1–634.

Vuong, N.V., Tich, V.V. and Bent, H. (2004) The application of the U-Pb TIMS method to the analyses of the crystallization age of Dai Loc massif. Vietnam Journal of Earth Sciences, 26, 202–207 (in Vietnam with English abstract).

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Quadt, A.V., Roddick, J.C. and Spiegel, W. (1995) Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards and Geoanalytical Research, 19, 1–23.

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