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U-Pb age and Lu-Hf isotopic characteristics of S-type granite in the Bac Tra My area, Quang Nam and their regional tectonic implications

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ABSTRACT

The Kon Tum Massif (KTM) in central Vietnam is a key part of the Indochina Block, where Early Paleozoic magmatism is attributed to subduction and subsequent collision between the KTM and the Truong Son Belt (TSB). However, the timing, source and tectonic setting of S-type granites of the Chu Lai Complex, especially near Bac Tra My area, remain unclear. This study presents new zircon U-Pb geochronological and Lu-Hf isotopic data from two granitic gneiss samples of the Chu Lai Complex in the Tra My area to better constrain their formation age, magma source and tectonic implications. Zircon U-Pb dating by MC-LA-ICP-MS yields concordant crystallization ages of 438.7 ± 2.9 Ma and 441.7 ± 1.9 Ma, corresponding to the Late Ordovician. Inherited zircon core ages (1.45÷2.62 Ga) indicate that the magma was derived from partial melting of Paleoproterozoic-Mesoproterozoic metasedimentary sources. Zircon εHf(t) values from -11.1to -2.4 support derivation from ancient crustal materials. Petrographic features, including muscovite, garnet and tourmaline, further indicate an S-type peraluminous affinity. Integrating these data with previous results suggests that Chu Lai magmatism (455÷426 Ma) represents a syn- to post-collisional episode following the closure of the Proto-Tethys Ocean and the collision between the KTM and the TSB. This event, likely during the Middle to Late Ordovician, marks the termination of subduction beneath the KTM and the onset of a widespread post-collisional thermal regime across the Indochina Block. The study refines the timing of Early Paleozoic orogenesis in central Vietnam, provides new isotopic evidence for the crustal evolution of the KTM and contributes to a better understanding of the tectonic assembly of the eastern Indochina Block during the Paleozoic.

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1. Introduction

The Viet-Cam Terrane and the Viet-Laos Terrane were accreted through subduction and subsequent collisional orogeny during the Early Paleozoic, ultimately forming the present configuration of the main Indochina Block (e.g., Tran et al., 2014; Tran et al., 2020). The boundary between the Viet-Cam Terrane and the Viet-Laos is generally considered to correspond to the Tam Ky-Phuoc Son suture zone (TPSZ) in central Vietnam, although its continuation westward remains debated (e.g., Faure et al., 2018). The Viet-Cam Terrane encompasses the core of the KTM, extending southwestward into Cambodia, while its eastern and southeastern margins may have subsided beneath the present-day East Sea (Tran et al., 2020). The TPSZ is extended to the west along the Po Ko zone (Tran et al., 2014; 2020; 2023), however, some studies argue that this zone may instead represent a Cenozoic strike-slip fault (Faure et al., 2018) and the TPSZ could be linked with the Thakhet-Da Nang fault (Figure 1a; Thassanapak et al., 2018). Although the Tam Ky-Phuoc Son suture zone and the Viet-Cam and Viet-Laos Terranes have been extensively studied, the tectonic evolution of the Chu Lai Complex in the central Kon Tum Massif remains poorly constrained. This study focuses on the Tra My area, providing new insights into S-type granitoid formation and regional tectonic interactions, thereby advancing our understanding of Early Paleozoic tectonics in the eastern Indochina Block.

Within the Indochina Block, Early Paleozoic magmatic and metamorphic rocks are extensively distributed, most prominently in the KTM (Figure 1a). These thermo-tectonic events have been interpreted as the consequence of the subduction of the Proto-Tethys oceanic lithosphere beneath both the KTM and the TSB, followed by subsequent collisional processes between these two blocks. Recent studies have demonstrated that subduction during the Cambrian-Ordovician triggered widespread arc-related magmatism, dated at ca. 520÷460 Ma in the TSB and ca. 488÷462 Ma in the KTM (e.g., Ngo et al., 2022; Nguyen et al., 2021; 2022). Granitoids of the

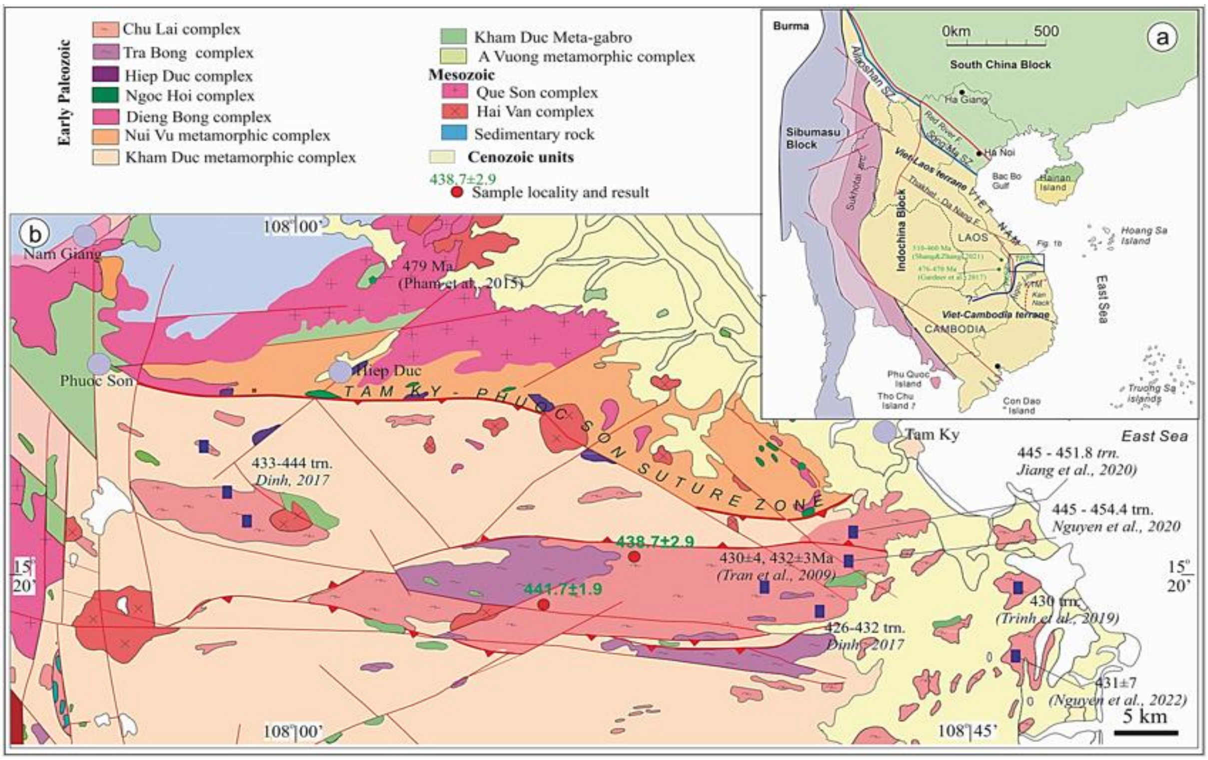

Figure 1. (a) Simplified tectonic features of Southeast Asia showing the Viet-Laos terrane and Viet-Cambodia terrane, Tam Ky - Phuoc Son Sture (TPSZ) (after Tran et al., 2014; 2020). (b) Simplified geological distributions across the TPSZ in Vietnam (After Ngo et al., 2022, 2025 a, b and references therein) showing the sample localities and U-Pb age dating results.

Chu Lai Complex are exposed mostly along the northern and western margins of the KTM, yielding U-Pb zircon ages of 455÷430 Ma (Jiang et al., 2020; Ngo et al., 2025b). Geochemical signatures and zircon Lu-Hf isotopes suggest that these granites formed in syn- to post-collisional settings, directly related to the Early Paleozoic orogeny between the KTM and the TSB (Jiang et al., 2020; Tran et al., 2020; Ngo et al., 2025b).

Previous geochronological and Lu-Hf isotopic studies of the Chu Lai Complex have so far been concentrated mainly on the northeastern KTM, while its central parts (e.g., Tra My area) remain poorly investigated. Due to this spatial bias, the magmatic evolution of the Chu Lai Complex as a whole is still not fully constrained and debates continue regarding its precise formation age, the nature of its magma source and its role in the tectonic evolution of the Indochina Block. In this study, we present new integrated data including field observations, petrography, zircon U-Pb geochronology and Lu-Hf isotope analyses from Chu Lai granitic intrusions in the Tra My area. Our aim is to determine the crystallization age and magma source of the Chu Lai granitoids in Tra My, to assess their relationship with the northeastern and western counterparts of the Chu Lai Complex and ultimately to evaluate their tectonic significance for the Early Paleozoic evolution of the Indochina Block.

2. Regional geology and sample description

The KTM, located in Central Vietnam, is composed of Precambrian meta-sedimentary and meta-magmatic rocks of the Kan Nack, Ngoc Linh and Kham Duc complexes, together with Early Paleozoic to Mesozoic sedimentary, metamorphic and magmatic rocks, which is consequently covered by Cenozoic volcanic-sedimentary sequences (Tran, 2023). Based on lithological features and metamorphic grade, the KTM is subdivided into three major tectonic assemblages: the Kan Nack, Ngoc Linh and Kham Duc assemblages (Figure 1b; Tran et al., 2023; Nakano et al., 2013; Usuki et al., 2009). Amphibolite- to granulite-facies metamorphic rocks of the Kan Nack and Ngoc Linh assemblages have been constrained to metamorphic conditions of ~570÷700 ^{0}C and ~7.9÷8.6 kbar during the Early Paleozoic (~420÷468 Ma; Roger et al., 2001; Nakano et al., 2013; Osanai et al., 2008) and were overprinted by Permian-Triassic metamorphism (Bui et al., 2020; Usuki et al., 2009). In the Kham Duc assemblage, metamorphic rocks mainly record greenschist- to amphibolite-facies conditions. A clockwise P-T path, from an early high-pressure/low-temperature metamorphism (M1) to a later low-pressure/high-temperature stage (M2), has been documented in amphibolite-facies rocks from the Tra My area (Usuki et al., 2009). U-Pb ages of metamorphic zircon rims have been constrained at ca. 447÷452 Ma, whereas Ar-Ar mica ages are 254÷225 Ma.

Within the KTM, gabbro-diorite, diorite and granodiorite of the Dien Binh Complex yield ages of 488÷426 Ma. Among them, gabbro-diorite and diorite from Dak Blo, Kon Tum and Quang Ngai, dated at 485÷460 Ma, are interpreted as products of continental arc magmatism related to subduction of the Proto-Tethys oceanic lithosphere beneath the KTM during the Early Paleozoic (Nguyen et al., 2021; 2024). In contrast, granitoids of the Chu Lai Complex (ca. 455÷426 Ma) are interpreted as syn- to post-collisional products (Figure 1b; Jiang et al., 2020; Ngo et al., 2021a, b, 2022, 2025b).

In the northern and southwestern KTM, the Chu Lai Complex forms large batholiths from Chu Lai to Phuoc Thanh and Dak To (Kon Tum) and is classified as S-type granite (Jiang et al., 2020; Ngo et al., 2025b). In addition, smaller intrusive bodies occur sporadically in Quang Ngai, Quang Nam and Kon Tum provinces. U-Pb zircon LA-ICP-MS dating of rocks from the eastern and northeastern KTM yields ages of 426-444 Ma in southern Quang Ngai (Dinh, 2017; Nguyen et al., 2022; Trinh et al., 2019), whereas granitoids from Nui Thanh (Quang Nam) yield ages of 445-452 Ma (Jiang et al., 2020). Whole-rock geochemistry and zircon Lu-Hf isotopes indicate that the Chu Lai granitoids are S-type granites formed during syn-collisional stage between the KTM and the TSB. Granitoids from Dak To yield U-Pb zircon ages of 445.4 and 427.5 Ma, interpreted as S-type magmatism related to post-collisional event (Ngo et al., 2025b). Based on the tectonic setting and ages of the Chu Lai Complex, previous studies have suggested that the collision between the KTM and TSB occurred before 455 Ma along the Tam Ky-

Phuoc Son and Po Ko suture zones (e.g., Jiang et al., 2020; Ngo et al., 2025b). North of the TPSZ, Middle Cambrian - Middle Ordovician volcanic-sedimentary sequences of the A Vuong Formation are unconformably overlain by the Middle Ordovician - Middle Silurian Long Dai Formation (Tran, 2023). Furthermore, rocks of the A Vuong Formation are intruded by granitoids of the Dai Loc Complex, producing metamorphic aureoles (Tran, 2023). The Dai Loc Complex, consisting of S-type granitoids, crops out as a large batholith with porphyritic, gneissic and augen structures (Jiang et al., 2020; Nguyen et al., 2021). Zircon U-Pb dating shows that Dai Loc granites are younger than Chu Lai granites, with ages of 427-407 Ma (Jiang et al., 2020; Nguyen et al., 2021) and are interpreted as post-collisional magmatism related to Late Ordovician orogeny between the KTM and TSB.

The Chu Lai Complex has been mapped as Neoproterozoic-Early Paleozoic on the 1/50,000 Tra My-Tac Po (e.g., Nguyen, 1996), although no precise geochronological data are available. Here, the geology is dominated by amphibolite intercalated with mica schist, quartz-mica-sillimanite schist and marble lenses of the Early Paleozoic Kham Duc Complex (Ngo et al., 2021b, c, d, 2022, Figure 1a, b). These rocks are mostly of greenschist-facies grade, with minor granulite-facies lenses. U-Pb zircon rim ages of amphibolite-facies rocks from Phuoc Son yield metamorphic ages of ca. 447÷452 Ma (Usuki et al., 2009). Monazite U-Th-Pb dating of metamorphic rocks from Phuoc Son gives ages of ca. 465 Ma, whereas the Tra My area and surroundings mainly record younger metamorphism at ca. 228÷238 Ma (Nakano et al., 2013). Meta-diorite lenses within the Kham Duc Complex of Bac Tra My yield LA-ICP-MS zircon U-Pb ages of 449÷450 Ma (Ngo et al., 2022).

3. Methods

3.1. Field and petrological Study

Geological fieldwork was conducted in the Trà My area (Quảng Nam province) to investigate granitoids of the Chu Lai Complex. Outcrops along the DT616 road near Trà Tân commune were systematically examined to document lithological variations, structural features and contact relationships with surrounding units. At each site, fresh and representative samples of granitoids were collected for petrographic, geochronological and isotopic analyses. The collected samples were selected to represent the main lithological types and deformation features observed in the field, ensuring their suitability for zircon separation and subsequent U-Pb dating and Lu-Hf isotope analyses. Petrographic studies were carried out on thin sections prepared from selected samples. These field and petrological observations provided the basis for selecting appropriate samples for zircon separation, U-Pb geochronology and Lu-Hf isotope analysis.

3.2. U-Pb age dating

Rock samples weighing 2÷3 kg were collected, crushed and subjected to water separation and heavy liquid techniques to concentrate heavy minerals. Zircon grains were then handpicked from the heavy mineral separates and mounted together with zircon standards for reference. The mounts were polished to expose the internal sections of zircon grains for analysis. Before measurement, zircon grains were imaged under reflected light and their internal textures were recorded using cathodoluminescence (CL) imaging with a JEOL 6610LV scanning electron microscope at the Ochang Center, Korea Basic Science Institute (OC-KBSI).

U-Pb zircon dating was conducted using MC-LA-ICP-MS at OC-KBSI, following the analytical procedures of Lee et al. (2018). A laser beam with a spot size of ~30 μm was applied for each measurement. To determine the magmatic crystallization age of the studied samples, all analyses targeted idiomorphic zircon zones or overgrowth rims, while inherited cores were excluded from dating. Zircon standards 91500 and Plesovice were used. Common lead correction was applied using Andersen's (2002) Excel program. Concordia plots and weighted software (Ludwig, 2008) and all ages are reported with 95% confidence intervals (2σ). Analytical results are presented in Table 1.

3.3. Lu-Hf isotopic analysis

Table 1. U-Pb isotopic age analysis of S-type granitic samples from Tra My area (Sample numbers are shown).

Analytical point	Isotopic Ratio						Age (Ma)		Th/U
	$^{207}Pb/^{235}U$	2 σ	$^{206}Pb/^{238}U$	2 σ	$^{207}Pb/^{206}Pb$	2 σ	$^{206}Pb/^{238}U$	2 σ	
Sample	CLTM-7								
7.1	0.5299	0.0106	0.0691	0.0009	0.0561	0.0008	430.5	6.1	0.9
7.2	0.5610	0.0195	0.0718	0.0017	0.0551	0.0017	446.4	9.3	0.7
7.3	0.5480	0.0370	0.0719	0.0015	0.0560	0.0037	447.7	9.2	1.1
7.4	0.5334	0.0098	0.0695	0.0008	0.0560	0.0010	432.8	6.4	1.5
7.5	0.5340	0.0180	0.0691	0.0009	0.0571	0.0025	430.8	6.1	0.5
7.6	0.5339	0.0168	0.0692	0.0009	0.0567	0.0025	431.3	6.2	0.4
7.7/1	0.5350	0.0120	0.0700	0.0009	0.0562	0.0011	436.2	5.6	0.9
7.7/2	3.6312	0.0270	0.2727	0.0018	0.09621	0.00036	1554.1	9.3	1.4
7.8	0.5360	0.0190	0.0702	0.0013	0.0562	0.0019	437.4	8.1	0.7
7.9	0.5466	0.0106	0.0715	0.0011	0.0559	0.0003	438.9	7.0	0.5
7.10	0.5530	0.0074	0.0717	0.0008	0.0557	0.0004	440.6	4.7	0.4
7.11/1	0.5595	0.0165	0.0719	0.0015	0.0550	0.0014	447.1	8.7	0.5
7.11/2	3.759	0.044	0.2856	0.0032	0.09517	0.00027	1619	16	0.3
7.12	0.5603	0.0110	0.0721	0.0011	0.0558	0.0007	444.4	6.9	0.6
7.13	0.5566	0.0097	0.0726	0.0010	0.0559	0.0005	446.1	5.2	0.7
7.14	0.5350	0.0110	0.0698	0.0008	0.0563	0.0010	435.0	6.1	0.7
7.15	0.5355	0.0155	0.0701	0.0011	0.0562	0.0015	436.8	6.9	0.8
7.16	0.5645	0.0195	0.0717	0.0016	0.0559	0.0016	445.7	8.4	0.6
7.17	0.5465	0.0120	0.0707	0.0011	0.0555	0.0009	440.2	6.4	0.5
7.18	0.5550	0.0145	0.0712	0.0012	0.0555	0.0011	443.1	7.1	0.7
Sample	CLTM-8								
8.1	0.5380	0.0265	0.0703	0.0019	0.0572	0.0024	437.7	8.4	1.0
8.2	0.5545	0.0088	0.0718	0.0009	0.0557	0.0005	441.0	5.6	1.0
8.3	0.5555	0.0260	0.0719	0.0014	0.0558	0.0025	447.6	8.6	0.9
8.4	0.5561	0.0100	0.0719	0.0010	0.0560	0.0007	443.4	5.9	0.6
8.5/1	0.5592	0.0126	0.0729	0.0013	0.0559	0.0006	447.6	6.4	0.5
8.5/2	3.1680	0.0340	0.2521	0.0022	0.09108	0.00051	1449	11	0.2
8.6	0.5607	0.0107	0.0722	0.0010	0.0561	0.0007	447.3	6.1	0.8
8.7	0.5636	0.0112	0.0722	0.0011	0.0559	0.0005	446.8	6.9	0.5
8.8	0.5425	0.0089	0.0712	0.0007	0.0557	0.0006	437.5	4.7	0.9
8.9	0.5430	0.0235	0.0705	0.0018	0.0570	0.0019	438.9	7.5	0.6
8.10/1	0.5435	0.0096	0.0713	0.0009	0.0558	0.0005	438.1	5.7	0.6
8.10/2	12.3300	0.1700	0.5004	0.0067	0.17935	0.00041	2620	28	
8.11	0.5445	0.0104	0.0714	0.0011	0.0558	0.0004	438.6	6.8	0.8
8.12	0.5497	0.0109	0.0719	0.0010	0.0558	0.0007	441.5	5.6	0.7
8.13	0.5510	0.0099	0.0717	0.0011	0.0559	0.0004	440.7	6.4	0.8
8.14	0.5519	0.0069	0.0719	0.0007	0.0558	0.0004	441.3	4.1	1.1
8.15	0.5534	0.0090	0.0719	0.0009	0.0558	0.0005	442.2	5.6	0.9

The Hf isotopic compositions of zircon were measured using the same instrument and the laser beam size of ~40÷50 μm used for each spot analysis overlapped the U-Pb dating spot. The analytical condition and data acquisition procedure were similar to those described by Kee et al. (2019). The instrument parameters were set to be a 10 Hz repetition rate and energy density of 6÷8 J/cm^2. He (650 mL/min) and N_2 (2 mL/ min) were used as carrier gases for higher Hf isotope intensity (e.g., Iizuka and Hirata, 2005). All the data reduction was conducted using the Iolite 2.5 software (Paton et al. 2011). Calculation of the initial $^{176}Hf/^{177}Hf$ and εHf(t) values was based on the Chondritic reservoir (CHUR) at the time of zircon crystallization and the measured isotopic compositions of zircon from the analyzed samples, assuming the ^{176}Lu decay constant (1.865×10-11 year^{-1}; Scherer et al., 2001), $(^{176}Hf/^{177}Hf)_{CHUR}$ ratio (0.282772; Blichert-Toft and Albarede, 1997) and $(^{176}Lu/^{177}Hf)_{CHUR}$ ratio (0.0333; Blichert-Toft and Albarede, 1997). Analytical results are listed in the Supplementary Table 2.

Table 2. Hf isotopic composition of zircon from sample CLTM-7.

Sample	$^{176}Hf/^{177}Hf$	2σ	$^{176}Lu/^{177}Hf$	2σ	$^{176}Yb/^{177}Hf$	2σ	Hf i	εHf(t)	$T_{(DM)}^{C}$
7.3	0.28225	0.00007	0.00131	0.00001	0.04868	0.00038	0.28	-8.84	1.98
7.5	0.28234	0.00008	0.00155	0.00004	0.05947	0.00112	0.28	-5.82	1.79
7.6	0.28219	0.00009	0.00181	0.00005	0.06928	0.00118	0.28	-11.09	2.12
7.8	0.28222	0.00006	0.00081	0.00002	0.02976	0.00036	0.28	-9.97	2.05
7.15	0.28243	0.00006	0.00050	0.00001	0.01755	0.00034	0.28	-2.35	1.58
7.16	0.28240	0.00007	0.00116	0.00002	0.04192	0.00076	0.28	-3.72	1.66

4. Results

4.1. Field and petrological features

In the Tra My area, granitoids of the Chu Lai Complex occur along the DT616 road near Tra Tan commune, Bac Tra My district, Quang Nam province. The northern margin of the complex is tectonically bound by a normal fault against metamorphosed sedimentary rocks of the Kham Duc Complex (Figure 2a). Magmatic rocks near the contact exhibit mylonitic structures, while those further inside the complex display banded or gneissic textures, commonly associated with small-scale folds (Figure 2b). Samples were collected from gneissic granitoids in the Tra Tan area, Bac Tra My district. Under the microscope, the mineral assemblage consists of quartz (30÷45%), K-feldspar (35÷40%), plagioclase (20÷30%), biotite (5÷10%) and muscovite (3÷5%) (Figure 2c). Muscovite is relatively abundant, whereas garnets and tourmalines occur only rarely in the samples studied.

4.2. U-Pb age analytical result

Zircon grains from the two Chu Lai granite samples are mostly euhedral to subhedral with prismatic morphology, transparent, pale yellow to colorless. Most exhibit clear magmatic zoning, while some show inherited cores (15 out of 100 CL-imaged grains from both samples) overgrown by euhedral zircon rims (Figure 3a, b). Analytical results show that Th/U ratios of euhedral zircon or rim zones range from 0.4÷1.5 (Table 1).

Eighteen zircon analyses from the granitic gneiss sample CLTM-7CL24 plot on the Concordia curve (Figure 3a), yielding $^{206}Pb/^{238}U$ ages from 430.5 ± 6.1 Ma to 447.7 ± 9.2 Ma, with a weighted mean $^{206}Pb/^{238}U$ age of 438.7 ± 2.9 Ma (MSWD = 3.1). Two analyses from inherited zircon cores give $^{206}Pb/^{238}U$ ages of 1554.1 Ma and 1619.0 Ma, representing detrital zircon from a late Mesoproterozoic source.

Fifteen zircon analyses from sample CLTM-8 also fall on the Concordia curve, giving $^{206}Pb/^{238}U$ ages between 437.5 ± 4.7 Ma and 447.6 ± 6.4 Ma, with a weighted mean $^{206}Pb/^{238}U$ age of 441.7 ± 1.9 Ma (MSWD = 1.3; Figure 3b). Two inherited zircon cores yield $^{206}Pb/^{238}U$ ages of 1449.0 Ma and 2620.0 Ma, suggesting sources from the late Paleoproterozoic and Mesoproterozoic.

4.3. Lu-Hf zircon analytical result

The six spot analyses of magmatic zircon grains from sample CLTM-7 yielded $^{176}Hf/^{177}Hf$ ratios between 0.28219 and 0.28243. The corresponding εHf(t) values range from -11.10 to -2.35, with a weighted mean of -6.2±3.7 (Figure 4).

5. Discussion

5.1. Origin and formation age of the Chu Lai Complex on the northern and western margin of the Kon Tum Massif and the source of Chu Lai granites

Petrographically, the studied samples commonly contain Al-rich silicate minerals such as muscovite, garnet and tourmaline, together with their low εHf(t) values which are characteristic of S-type granites. Muscovite and garnet are Al-rich minerals that only occur in S-type granites derived from partial melting of sedimentary rocks. The Chu Lai Complex has been described as metatexite rocks (consisting of leucosome (light-colored domains) and melanosome (dark-colored domains)) formed by high-grade metamorphism and partial melting of ancient sedimentary rocks (e.g., Ngo et al., 2025b). The abundance of inherited zircon cores in the analyzed samples, with ages ranging from

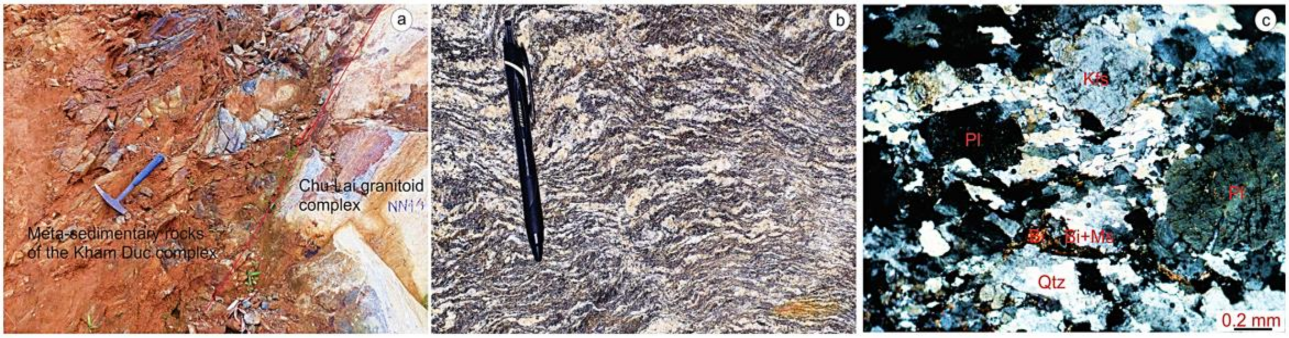

Figure 2. (a) Representative field photo shows the normal fault bounded the S-type granite and metamorphic Kham Duc complex; (b) The occurrence of the Chu Lai complex in the Tra My area; (c) photomicrographs under cross-polarized light showing the representative textures and mineral composition of the gneissic granite. Abbreviations: Qtz, Quartz; Pl, plagioclase; Kfs, K-feldspar; Bt, Biotite; Ms, Muscovite.

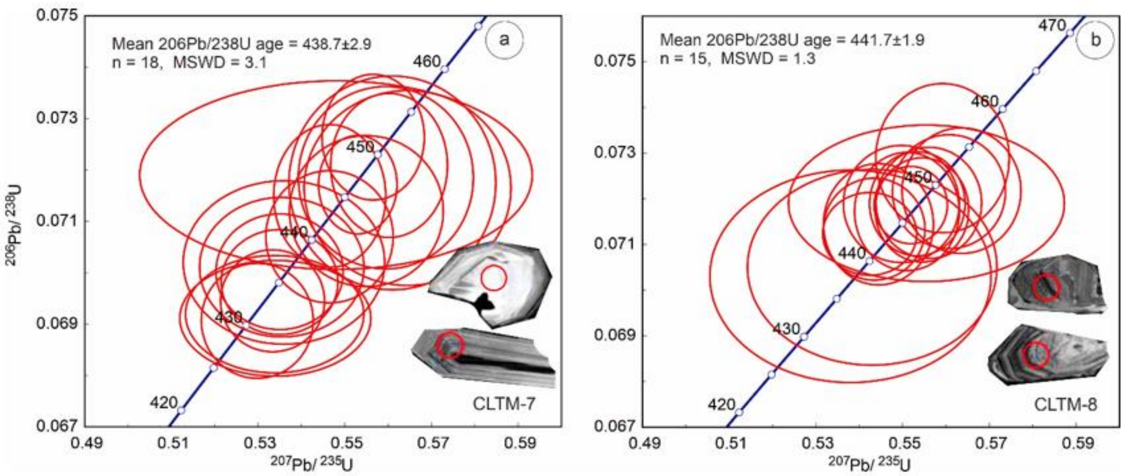

Figure. 3. Representative Cathodoluminescence (CL) images of the analyzed zircon grains and 206Pb/238U vs. 207Pb/235U Concordia diagrams showing the mean 206Pb/238U ages of the analysis samples CLTM-7 (a) and CLTM-8 (b).

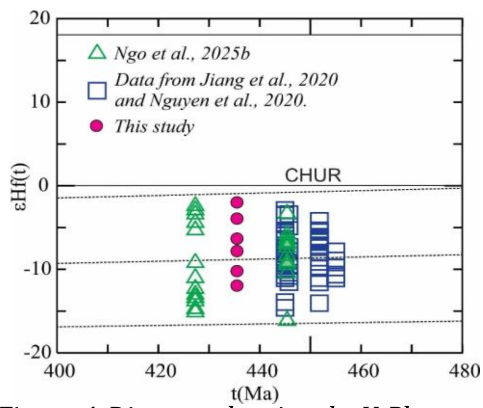

Figure. 4. Diagram showing the U-Pb age vs. εHf(t) value of zircon from sample CMTM-7. Data from the Chu Lai complexes in the northeast of KTM (Jiang et al., 2020; Nguyen et al., 2020; Ngo et al., 2025 b) is plotted for comparison.

Mesoproterozoic to Paleoproterozoic, further indicates that the studied magmas originated from melting of sedimentary protoliths with diverse sources, consistent with previous studies on the Chu Lai Complex magmatism in Chu Lai and Dak To areas (Jiang et al., 2020; Nguyen et al., 2020; Ngo et al., 2025b). These lines of evidence suggest that the studied magmatic rocks belong to S-type granites derived from partial melting of ancient Paleo- to Meso-Proterozoic sediments.

The main body of the Chu Lai Complex is distributed along the northern margin of the Kon Tum Massif (KTM). Previously, the age of the Chu Lai Complex was determined by the whole-rock Rb-Sr isotope method (~530 Ma) and by U-Pb TIMS zircon dating, yielding ages of ~772 Ma and ~515 Ma (Tran, 2023 and references therein).

Based on these results, granitic rocks of the Chu Lai Complex were classified as Neoproterozoic to Early Paleozoic (Tran, 2023).

Our study of two Chu Lai granitic samples from the Tra My area yielded $^{206}Pb/^{238}U$ ages of 438.7 ± 2.9 Ma and 441.7 ± 1.9 Ma, corresponding to the Late Ordovician. These ages were obtained from zircon grains with idiomorphic overgrowth rims, with Th/U ratios of 0.37÷1.5, typical of magmatic zircons. Since zircon is resistant under metamorphic conditions, with a high closure temperature for the U-Pb system (>900°C; Cherniak & Watson, 2001), the obtained U-Pb ages (438.7 ± 2.9 Ma and 441.7 ± 1.9 Ma) are interpreted as the crystallization ages of the studied magmatic rocks.

Recent zircon U-Pb studies on Chu Lai granites, especially in the northeastern KTM, have yielded ages of ~444÷426 Ma (Dinh, 2017; Nguyen et al., 2022; Trinh et al., 2019) and 455÷445 Ma (Jiang et al., 2020; Nguyen et al., 2020). In the southeastern KTM, Chu Lai granites yielded ages of ~445÷427 Ma (Ngo et al., 2025b). Our U-Pb age and Lu-Hf zircon isotopic results are consistent with the previous data reported within the Chu lai Complex in the northeast and southwest KTM (e.g., Jiang et al., 2020; Nguyen et al., 2022; Ngo et al., 2022). Up to now, a large number of samples analyzed across the Chu Lai Complex within the KTM, it is clear that the magmatism occurred during a period from the Late Ordovician to the Silurian (Wenlock; Figure 5).

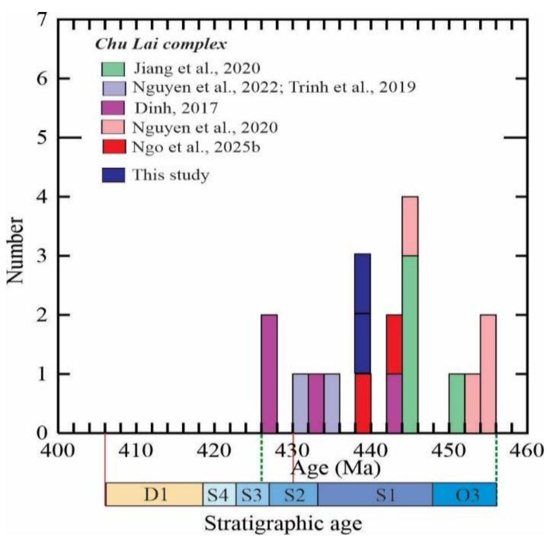

Figure. 5. Histograms U-Pb age magmatic zircons in the Chu Lai granitic gneiss (D Devonian; S: Silurian; O: Late Ordovician).

These ages are significantly younger than the previously reported Neoproterozoic-Early Paleozoic ages often used in 1:50,000 geological mapping. Furthermore, they indicate that magmatism of the Chu Lai Complex lasted longer than recently suggested (Tran, 2023), representing a syn- to post-collisional magmatic stage related to the convergence between the Kon Tum Massif and the Truong Son Belt.

5.2. Geological implications

The Viet-Laos and Viet-Cam Terranes are considered as two distinct microcontinents located along the northern margin of East Gondwana during the Neoproterozoic-Early Paleozoic (Ngo et al., 2025a). Subduction of the Proto-Tethys Ocean beneath the KTM during the Early to Middle Ordovician (Ngo et al., 2025a) and the subsequent closure of this oceanic basin, led to continental collision and orogeny, contributing to the assembly of the eastern Indochina Block in the Early Paleozoic. The presence of mafic to felsic magmatic rocks dated at 520÷460 Ma in the TSB and 485÷470 Ma in the KTM has been interpreted as related to subduction processes beneath the TSB and KTM during those times (Gardner et al., 2017; Nguyen et al., 2019; 2021; 2024; Ngo et al., 2022, 2025b). Furthermore, mafic to ultramafic rocks of the Hiep Duc and Plei Wek complexes along the Tam Ky-Phuoc Son and Po Ko shear zones are considered remnants of ancient oceanic lithosphere, representing ophiolitic mélanges along the suture zones (Tran et al., 2020). Thus, previous studies have supported the existence of a paleo-ocean between KTM and TSB, which was eventually consumed along the Tam Ky-Phuoc Son Suture Zone in the Early Paleozoic.

However, the timing of collision between KTM and TSB remains debated. Gardner et al. (2017) suggested ~430 Ma, Jiang argued for ~455 Ma, while Tran et al. (2020) and Ngo et al. (2025a, b) proposed that collision occurred at least ~460÷470 Ma. It is well established that S-type granites commonly form in syn- to post-collisional tectonic settings, especially during extensional stages following collision (Harris et al., 1986; Sylvester, 1998). The widespread occurrence of S-type granites in the KTM and across Indochina during the Late Ordovician-Early Silurian suggests extensive sediment-derived magmatism during this time, reflecting a tectonic event that influenced the entire Indochina Block.

Geochemical data from the Chu Lai Complex further indicate that these granites were generated in a post-collisional tectonic environment (Ngo et al., 2025b). The occurrence of post-collisional Chu Lai granites dated at 455÷430 Ma within the KTM suggests that closure of the paleo-ocean between TSB and KTM occurred before 455 Ma. This evidence reinforces the hypothesis that collision between KTM and TSB, possibly involving the entire Viet-Lao and Viet-Cambodia Terranes, took place by the Middle to Late Ordovician. This interpretation is supported by the presence of an unconformity between Late Ordovician-Middle Silurian Long Dai Formation sediments and the underlying Early Cambrian-Middle Ordovician A Vuong Complex (see Tran, 2023), indicating that the collision event occurred by the Middle Ordovician. In addition, high to ultrahigh-temperature metamorphic assemblages in the Ngoc Linh and Kan Nack complexes have yielded ages of 468÷430 Ma (Nakano et al., 2013), while amphibolite from the Tra My area records zircon rim ages of 447÷452 Ma related to metamorphism. These metamorphic events are interpreted as products of syn- to post-collisional tectonics between KTM and TSB.

Taken together with our new results, these findings confirm that subduction beneath the KTM (and possibly the TSB) ceased, followed by continental collision and orogenesis between the two crustal blocks during the Middle Ordovician. This represents a key tectonic event that sheds light on the formation and evolution of the Indochina Block. Moreover, it provides critical constraints for the subdivision of magmatic stages in Indochina, with implications for mineral exploration and resource assessment in Vietnam.

6. Conclusions and Recommendations

The integrated results of field observations, petrography, zircon U-Pb dating and Hf isotopic analyses provide new insights into the nature, timing and tectonic setting of the Chu Lai granitoids in the northern part of the KTM. These findings allow us to make three main conclusions as follows:

(1) Petrographic features, inherited zircon cores and negative εHf(t) values confirm that the Chu Lai granitoids are S-type granites, derived from partial melting of Paleo- to Meso-Proterozoic sedimentary protoliths.

(2) New U-Pb zircon ages of ~439÷442 Ma together with published data, define a S-type magmatic episode lasting from ca. 455÷426 Ma across the Kon Tum Massif.

(3) The geochronological and geochemical evidence demonstrates that the Chu Lai granites formed in a syn- to post-collisional setting, implying that collision between the Kon Tum Massif and the Trường Sơn Belt occurred before ~445 Ma, a key event in the Early Paleozoic evolution of the Indochina Block.

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Contributions of authors

Thanh Xuan Ngo - data processing, conceptualization, manuscript writing and submission, responsible for scientific content; Khang Quang Luong - project leader; provided funding and data for the study, revised and contributed to the conceptual framework, reviewed and edited the manuscript; Hau Vinh Bui - participated in fieldwork, data analysis and data processing; Hien Thu Thi Bui - participated in fieldwork and data analysis; Hung Quoc Nguyen - participated in fieldwork and data analysis; Tuong Trong Dinh - participated in fieldwork and data analysis.

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