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Table of Contents

The Ngoc Linh Complex in Central Kon Tum Massif: an exposed remnant of the Early Paleozoic collisional tectonism in East Central Indochina mainland

Hai Thanh Tran, Truong Tai Nguyen, Hau Vinh Bui, Thanh Xuan Ngo, Monsup Cho, Chi Kim Ngo, Dao Anh Vu, Hiep Huu Nguyen, Binh Van Phan, Hung Quoc Nguyen..... 1

Late Cretaceous Magmatism in the Nui Sam Area (An Giang Province, Southwestern Vietnam): Implications for the Tectono-Magmatic Evolution of the Ankroet Complex

Bui Vinh Hau, Tran Thanh Hai, Nguyen Truong Tai, Ngo Thi Kim Chi, Phan Van Binh, Vu Anh Dao, Nguyen Huu Hiep, Nguyen Quoc Hung, Ngo Xuan Thanh 10

U–Pb zircon geochronology of meta-diorite in the Vit Thu Lu area, northern Quang Tri, central Vietnam

Dinh Trong Tuong, Nguyen Quoc Hung, Tran My Dung, Ha Tri Dung, Dang My Cung, Ngo Xuan Thanh 16

Post-collisional extension during the Early Paleozoic in Northeast Vietnam: Evidence from syenitic complex

Chu Van Dung, Tran My Dung, Ngo Xuan Thanh..... 23

Zircon U–Pb constraints on episodic magmatism of the Hai Van granitoid complex and implications for the Indosinian orogeny in central Vietnam

Dinh Trong Tuong, Ngo Xuan Thanh, Tran My Dung Ha Tri Dung 34

Controlling factors on mineralization in the Tram Tau felsic volcanic formation (Tu Le Basin, North Vietnam)

Tran Thi Huong, Nguyen Hoang, Tran Thanh Hai..... 42

Distribution and Metamorphic Evolution of REE-bearing Minerals in Metapelitic Rocks of the Nam Co Formation, Song Ma Suture Zone, NW Vietnam

Bui Vinh Hau 56

Technology for rare earth ore beneficiation in Vietnam

Thanh Hai Pham..... 63

Structural and tectonic controls on gold mineralization in the northern Kon Tum massif, Vietnam

Vu Tien Thanh, Nguyen Van Vuong, Luong Thi Thu Hoai 73

Potential for Marine Ion-Adsorption Rare Earth Deposits: Sedimentary Facies Controls in Southwestern Vietnam

Nguyen Huu Hiep, Phan Van Binh, Tran Thanh Hai, Bui Hoang Bac 85

Fluvial geomorphology and weathering crust controls on ion-adsorption rare earth element mineralization in Northwestern Vietnam

Dinh Thi Hue, Vu Anh Dao 93

Tectonic – Geomorphology and its relation to geo-hazards in the Southwest region of Vietnam

Nguyen Xuan Nam, Tran Thanh Hai, Ngo Thi Kim Chi, Hoang Ngo Tu Do, Vu Anh Dao, Nguyen Xuan Quang..... 100

Grain-size and mineralogical characteristics of surface sediments in the Con Co Island area and their environmental significance

<i>Phan Van Binh, Hoang Van Long, Le Anh Thang, Vu Anh Dao, Nguyen Huu Hiep, Nguyen Quoc Hung, Bui Vinh Hau, Vo Thi Cong Chinh, Nguyen Thi My Hanh.....</i>	<i>108</i>
Shoreline change assessment on Phu Quoc Island using Satellite Remote Sensing and the Digital Shoreline Analysis System (DSAS)	
<i>Ngo Thi Kim Chi, Tran Thanh Hai, Bui Minh Quan, Bui Vinh Hau, Phan Van Binh, Vu Anh Da¹, Nguyen Xuan Quang</i>	<i>117</i>
Geological characteristics of karst and their relationship to underground karst collapse in Quang Ninh province	
<i>Nguyen Xuan Nam, Nguyen Dinh Tuan, Doan Thi Ngoc Huyen</i>	<i>124</i>
Retaining Structures Using Gabion System: Case Examples to be Applied Further in Mining Engineering Projects	
<i>Phan Van Binh, Vu Anh Dao, Bui Vinh Hau, Nguyen Xuan Nam, Vo Thi Cong Chinh, Nguyen Thi Minh Thu</i>	<i>138</i>
Geological hazards at the main dam of Dap Troi reservoir, Ninh Binh Province, Vietnam	
<i>Ban To Xuan.....</i>	<i>150</i>
The erosion and accretion at Day River mouth, Vietnam	
<i>Ban To Xuan.....</i>	<i>161</i>
Spatio-temporal variation of agricultural drought based on SMAPI evaluation toward supporting water resources management in the Red River Basin	
<i>Nguyen Hoang Hiep, Nguyen Lan Huong, Tran Thi Phuong Linh, ...</i>	<i>179</i>
Landslide hotspot identification by instance-based learning: A comparison of k-nearest neighbour and the entropy-based distance algorithm (Kstar)	
<i>Minh Nhut Dao, Quoc Phi Nguyen, Duong Van Hoa</i>	<i>188</i>
Performance of stochastic inversion approaches of groundwater flow and heat transport modeling in parameter estimation	
<i>Doan Thi Thanh Thuy, Nguyen Hoang Hiep, Nguyen Bach Thao, Vu Thu Hien.....</i>	<i>203</i>
Environmental Issues of Rare Earth and Critical Mineral Mining in Vietnam	
<i>Quoc Phi Nguyen, Thi Mai Hoa Phan, Thi Cuc Nguyen, Quang Minh Nguyen, Van Binh Nguyen, Trung Thanh Dao, Minh Nhut Dao, Ha Tuan Anh, Khanh Phuong Mai.....</i>	<i>210</i>
Application of the remote sensing ecological index (RSEI) to assess ecological quality in Coal mining areas of Quang Ninh province, Viet Nam	
<i>Nguyen Thi Cuc, Phan Thi Mai Hoa, Nguyen Anh Hoa, Nguyen Van Bin</i>	<i>219</i>
Environmental vulnerability assessment for sustainable mining using GIS based AHP - VIKOR approach: A Case Study of Ha Quang, Cao Bang District, Vietnam	
<i>Phan Thi Mai Hoa, Nguyen Quoc Phi, Nguyen Thi Cuc</i>	<i>230</i>
Assessment of Hydrodynamic Changes Induced by Dredging and Sand Mining in Tra Ly Estuary for Sustainable Resource Management	
<i>Vu Thi Lan Anh, Nguyen Thi Hoa, Nguyen Thi Hong, Tran Thi Ngoc, Vu Van Ngoc, Nguyen Cham Anh, Nguyen Thi Thuy Hien, Phan Thi Mai Hoa.....</i>	<i>246</i>

Zircon U–Pb constraints on episodic magmatism of the Hai Van granitoid complex and implications for the Indosinian orogeny in central Vietnam

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ABSTRACT

Zircon U–Pb geochronology of granitoids from the Hai Van complex, central Vietnam, reveals two distinct magmatic episodes at 243.1 ± 1.0 Ma and 230.9 ± 1.5 Ma, indicating episodic magmatism during the Early–Middle Triassic. Zircon morphology and cathodoluminescence images show well-developed oscillatory zoning, confirming a magmatic origin. Combined with published geochemical and isotopic data, the granitoids are classified as S-type, characterized by high SiO₂ and alkali contents, depletion in Ba, Sr, and Ti, and pronounced negative Eu anomalies, suggesting derivation from partial melting of metasedimentary crust. Integration of new and published geochronological data indicates that the Hai Van granitoid complex formed over a period of ca. 243–224 Ma, reflecting episodic magmatic activity lasting at least ~10–15 Myr. This prolonged magmatism records sustained crustal reworking during the syn- to post-collisional stages of the Indosinian orogeny. The Hai Van granitoids are therefore interpreted as products of crustal anatexis associated with continental collision between the Indochina and Viet–Trung blocks, providing important constraints on the timing of magmatism and the geodynamic evolution related to the closure of the Palaeo-Tethys Ocean in central Vietnam.

Keywords: *Zircon U–Pb dating; S-type granite; episodic magmatism; Indosinian orogeny; central Vietnam*

1. Introduction

Southeast Asia is composed of multiple Gondwana-derived continental fragments that were progressively assembled during the Paleozoic to Mesozoic, forming part of the eastern Tethyan domain (Metcalfe, 1988, 1990; Lepvrier et al., 2004). In central Vietnam, the Truong Son belt represents the northeastern margin of the Indochina terrane and preserves key records of this tectonic evolution (Tran et al., 2020; Ngo et al., 2023, 2025a, b, 2026). Geochronological studies have identified two major episodes of magmatism and metamorphism in this region, corresponding to the Cambrian–Silurian and the Permian–Early Triassic (Nagy et al., 2001; Ngo et al., 2016; Tran et al., 2020; Ngo et al., 202025a, b, 2026). These events are widely expressed by granitoid intrusions and high-grade metamorphic rocks, reflecting multiple stages of crustal reworking within the Indochina terrane.

The Hai Van granitoid complex is a major intrusive body in central Vietnam, composed predominantly of granite with mineral assemblages including biotite, cordierite, and locally garnet and/or sillimanite (Thuc and Trung, 1995). These mineralogical characteristics are typical of S-type granitoids and suggest a dominantly crustal origin, commonly associated with orogenic settings. However, granitoid magmatism may form under a variety of tectonic regimes, and thus requires integrated geochronological and geochemical constraints to resolve its origin and geodynamic significance.

Early studies of the Hai Van complex relied mainly on K–Ar and Rb–Sr geochronology (Dovjikov, 1965; Thuc and Trung, 1995), which provide limited precision for constraining magma emplacement. More recent work by Pham et al. (2015) reported zircon U–Pb ages of ca. 242–224 Ma, indicating that the complex crystallized during the Late Permian to Early Triassic and corresponds to late- to post-orogenic magmatism. Geochemically, the granitoids are characterized by high SiO₂ and alkali contents, enrichment in Rb, Th, U, and Pb, and depletion in Ba, Sr, Nb, P, and Ti, together with pronounced negative Eu anomalies, indicative of feldspar fractionation during magma evolution. Their Nd–Hf isotopic signatures, marked by low $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values and Paleoproterozoic model ages (~1.9–1.7 Ga), further indicate derivation predominantly from reworked ancient crustal sources.

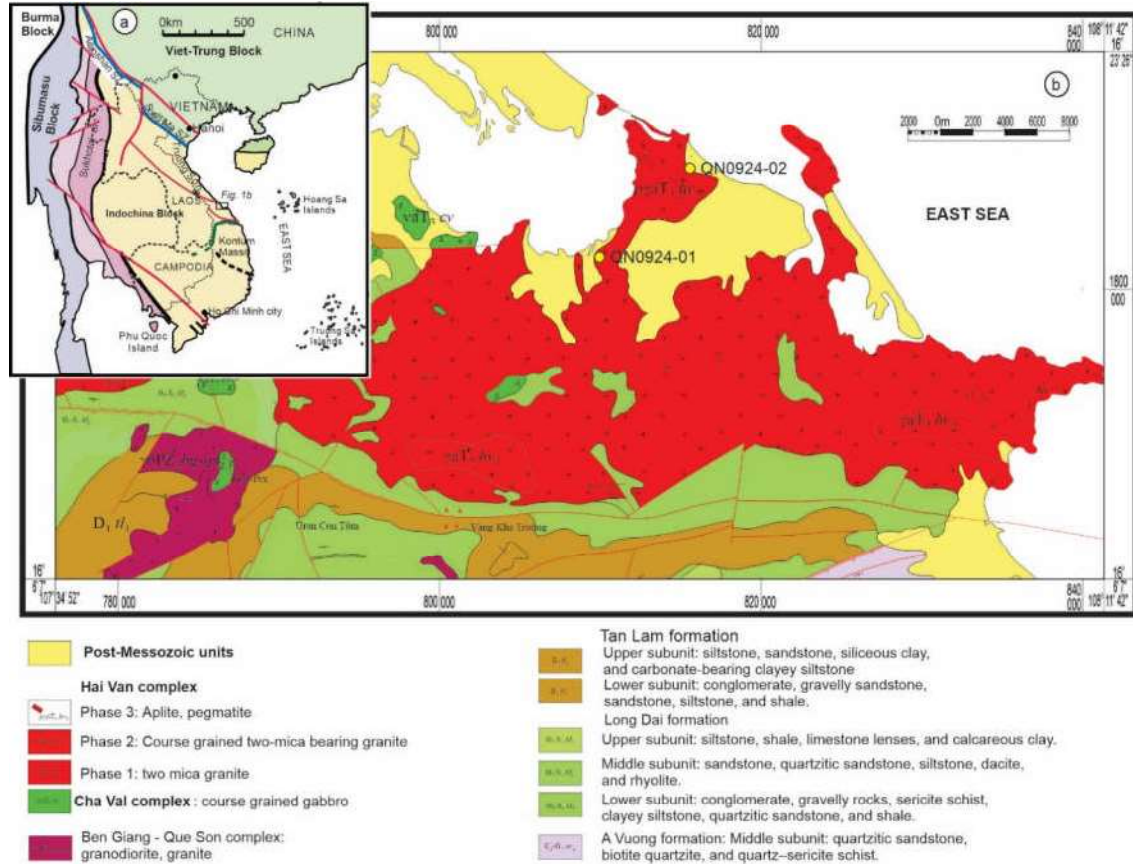


Figure 1. (a) General tectonic framework of Southeast Asia, showing the relationships among the Indochina, South China, and Sibumasu blocks, major suture zones, and large-scale fault systems; (b) Geological map of the study area, illustrating stratigraphic units, intrusive bodies, fault systems, and the sample localities.

Despite these advances, several key issues remain unresolved. In particular, the temporal evolution of magmatism within the Hai Van complex is still insufficiently constrained, and the extent to which magmatic activity was continuous or episodic remains unclear. Moreover, most previous studies have focused on limited sampling areas, whereas the southern segment of the Truong Son belt remains poorly investigated. This lack of data hampers a comprehensive understanding of the spatial variability of magmatism and its relationship to the Indosinian orogeny. In this study, we present new zircon U–Pb geochronological data from granitoid samples collected from the southern part of the Truong Son belt. The aims are to (i) better constrain the timing and duration of magmatism in the Hai Van complex, (ii) evaluate the

episodic nature of magma emplacement, and (iii) assess the implications for crustal reworking and tectonic evolution during the Indosinian orogeny. These new data, combined with published datasets, provide improved insights into the role of Triassic magmatism in recording the closure of the Palaeo-Tethys Ocean in central Vietnam.

2. Geological setting and samples

The Indochina terrane is bounded by the Song Ma suture to the north and the Nan–Uttaradit and Sra Kaeo sutures to the west, whereas its southern and eastern margins are adjacent to the East Sea (Biển Đông). The terrane is interpreted to have formed through the amalgamation of the Kon Tum block and the Truong Son orogenic belt along the Tam Ky–Phuoc Son suture zone (Tran et al., 2020; Ngo et al., 2023, 2025a, b, 2026, Figure 1b). The study area is located in the southern part of the Truong Son belt.

Regionally, the study area is dominated by Cambrian–Ordovician sedimentary sequences of the A Vuong Formation and Upper Ordovician–Silurian strata of the Long Dai Formation. These sedimentary units are intruded by Ordovician–Silurian granitoids belonging to the Dien Binh, Tra Bong, and Dai Loc complexes, which are widely interpreted as products of subduction-related magmatism during the Cambrian–Ordovician. This magmatic activity was followed by continental collision between the Kon Tum block and the Truong Son belt in the early Late Ordovician (Ngo et al., 2022, 2025a, b, 2026).

Permian–Triassic magmatic and sedimentary formations are also widely developed in the region. Permian magmatic rocks of the Ben Giang–Que Son complex are interpreted to be related to subduction processes (Nguyen et al., 2024), whereas Triassic granitoids of the Hai Van complex are considered to represent syn- to post-collisional magmatism associated with the convergence and eventual collision between the Indochina terrane and the Viet-Trung continental domain. Among these, the Hai Van complex represents a large, elongate plutonic body extending in a sublatitudinal direction and consisting of diverse granitoid lithologies such as biotite granite, granodiorite, two-mica granite, aplite, and cordierite-bearing granitoids (Thuc and Trung, 1995; Pham et al., 2015).

3. Analytical methods and results

3.1. Petrology

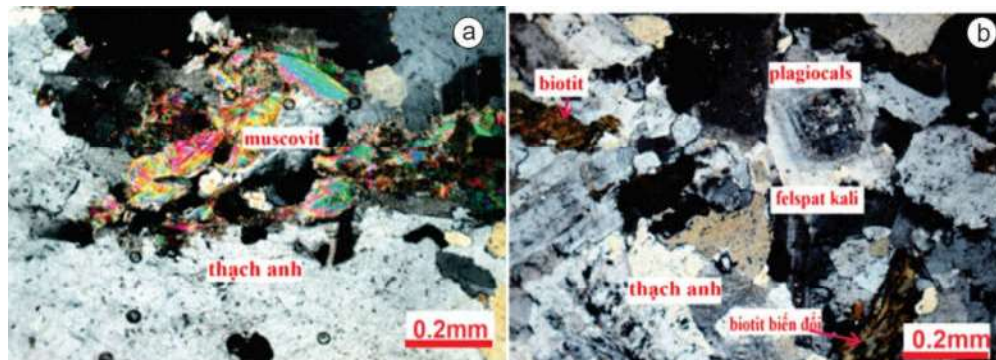


Figure 2. Photomicrographs of representative granitoids from the Hai Van complex under crossed-polarized light.

Granitoid samples from the Hai Van complex were collected from the Suoi Mo area (sample QN0924-01; 16°12'57.2"N, 108°02'03.6"E) and the Phu Gia tunnel area (sample QN0924-02; 16°15'54.9"N, 108°01'56.6"E) (Figure 1b). Petrographic characteristics were examined using standard thin sections under a polarizing microscope. The studied rocks are typically medium- to coarse-grained and grey to dark grey in colour due to the presence of smoky quartz, and locally exhibit weak foliation. Mineral assemblages are dominated by plagioclase, quartz, and biotite, with minor muscovite and/or cordierite. Accessory minerals commonly include zircon and apatite, as observed in thin sections. Representative photomicrographs illustrating the petrographic characteristics are shown in Figure 2a, b.

3.2. Zircon morphology and internal structures

Zircon grains from the studied samples are generally euhedral to subhedral and exhibit elongate prismatic morphologies, with grain sizes typically ranging from ~80 to 150 μm . Most crystals show well-developed crystal faces and aspect ratios of approximately 2:1 to 4:1, consistent with a magmatic origin.

Cathodoluminescence (CL) images reveal that the majority of zircon grains display well-defined oscillatory zoning, indicative of crystallization from a magma. The zoning patterns are generally clear and continuous, although some grains show slight variations in luminescence intensity, reflecting minor compositional changes during crystal growth. Locally, a few grains exhibit weakly developed cores surrounded by oscillatory-zoned rims, suggesting limited inheritance or early crystallization stages. Analytical spots are shown as red circles and are mainly positioned within the oscillatory-zoned domains, avoiding cracks and inclusions. These textural characteristics indicate that the analyzed zircons are predominantly of magmatic origin and that the obtained U–Pb ages reliably record the timing of magma crystallization.

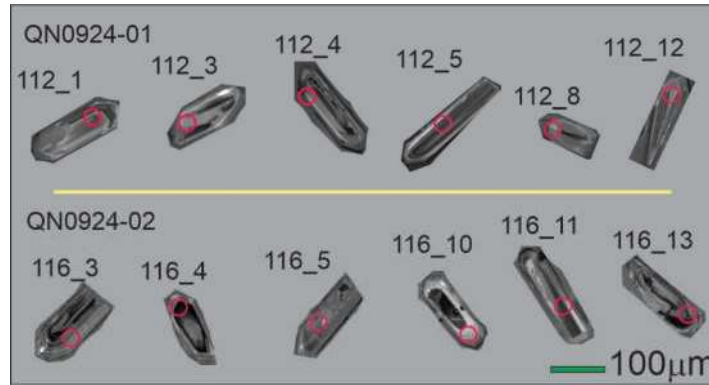


Figure 3. Cathodoluminescence (CL) images of representative zircon grains from the studied samples. Analytical spots are indicated by red circles. Scale bar = 100 μm .

3.3. Zircon U–Pb geochronology

Zircon U–Pb analytical results for samples QN0924-01 and QN0924-02 are shown in Figure 3. Most zircon analyses from both samples plot on or close to the concordia line, indicating negligible Pb loss and preservation of primary isotopic systematics. The sample QN0924-01, fifteen analyses define a coherent cluster and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 243.1 ± 1.0 Ma (MSWD = 0.54). The sample QN0924-02 yields sixteen analyses that form a near-concordant array, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 230.9

± 1.5 Ma (MSWD = 1.9). Although the MSWD is slightly elevated, the majority of analyses define a consistent age population, which is considered to represent the timing of zircon crystallization. Minor dispersion of some analyses may reflect limited isotopic disturbance or inheritance (Figure 4).

4. Discussions

4.1. Emplacement age and petrogenesis of the Hai Van complex

Zircon U–Pb data obtained in this study provide new constraints on the timing of emplacement of the Hai Van granitoid complex. Sample QN0924-01 yields a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 243.1 ± 1.0 Ma (MSWD = 0.54), whereas sample QN0924-02 gives a younger age of 230.9 ± 1.5 Ma (MSWD = 1.9). These results indicate that the Hai Van granitoids crystallized during two distinct magmatic episodes spanning from the Early to Middle Triassic. The older age at ca. 243 Ma is consistent with previously reported zircon U–Pb ages for the Hai Van complex (242–224 Ma; Pham et al., 2015) and likely represents the main phase of granitoid emplacement. This temporal distribution indicates that magmatism in the Hai Van complex was episodic rather than continuous, occurring over a period of at least ~10–15 Myr.

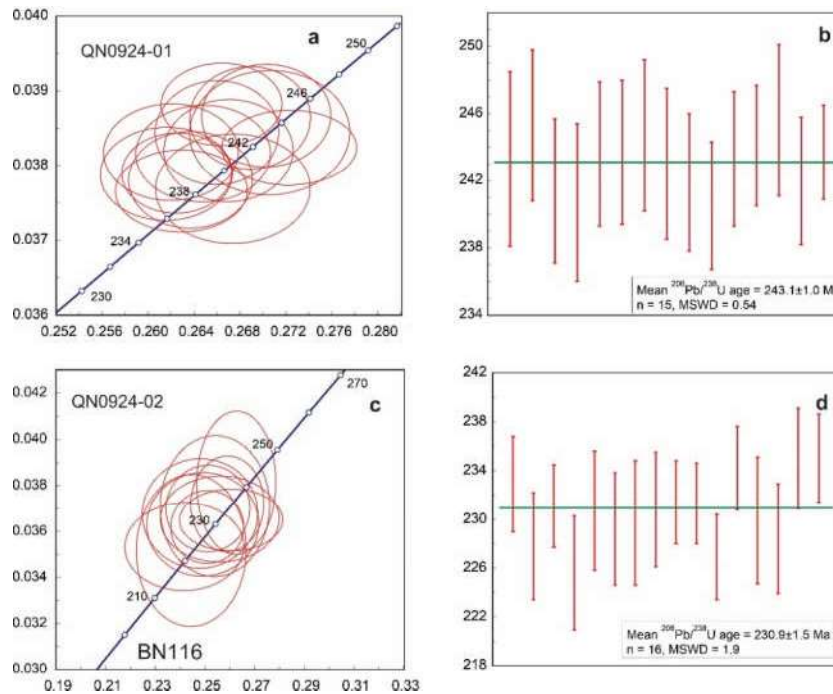


Figure 4. Concordia diagrams (a, c) and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages (b, d) for zircon from samples QN0924-01 and QN0924-02. Errors are 2σ .

Geochemical characteristics reported by Pham et al. (2015) indicate that the Hai Van granitoids belong to an S-type granite series, characterized by high SiO_2 and alkali contents, the presence of muscovite and cordierite, and strong depletion in Ba, Sr, and Ti together with pronounced negative Eu anomalies. The occurrence of magmatic muscovite identified in this study provides additional mineralogical evidence supporting an S-type affinity. These features suggest that the magma was generated predominantly by partial melting of crustal materials. Accordingly, the zircon U–Pb ages obtained here are interpreted to record the timing of crustal anatexis and subsequent magma emplacement.

Consequently, the Hai Van granitoid complex records a prolonged magmatic history related to the Indosinian orogeny in central Vietnam. The emplacement ages obtained in this study suggest that crustal melting and granitoid magmatism initiated during the late stages of continental collision and continued into the post-collisional regime. The Hai Van granitoids thus represent syn- to post-collisional S-type magmatism generated by partial melting of crustal materials during the final stages of the Indosinian tectonic evolution.

4.2. Tectonic implications for the Indosinian orogeny in central Vietnam

The new zircon U–Pb ages obtained in this study, combined with previously published geochronological and geochemical data, provide important constraints on the tectonic evolution of central Vietnam during the Indosinian orogeny. The crystallization age of ca. 243 - 231 Ma for the Hai Van granitoid complex overlaps with a period of widespread magmatism and high-grade metamorphism documented along the Song Ma suture zone and within the northern Kontum massif (e.g., Nakano et al., 2013; Bui et al., 2020). This temporal correspondence suggests that the Hai Van magmatism was closely associated with the late stages of continental collision. Regional geochronological data indicate that high-pressure metamorphism and related tectonothermal events in central Vietnam occurred at ca. 253–240 Ma (Nakano et al., 2013), marking the timing of collision between the Indochina Block and the Viet-Trung continental domain. In this context, the ~243 Ma age is interpreted to represent syn- to late-collisional magmatism related to crustal thickening and partial melting.

Regional geological evidence suggests that the Indosinian orogeny in Vietnam resulted from the convergence and eventual collision between the Indochina Block and the Viet-Trung continental domain following the closure of a branch of the Palaeo-Tethys Ocean. High-pressure metamorphic rocks, including eclogites and granulites, dated at ca. 250–240 Ma, mark the peak of collisional processes along the suture zone. The emplacement of the Hai Van granitoids at ca. 246–242 Ma therefore postdates or overlaps with peak metamorphism and likely corresponds to a syn- to late-collisional magmatic phase.

The S-type geochemical affinity of the Hai Van granitoids, as documented by Pham et al. (2015), further supports a collisional tectonic setting. Such granites are typically generated by partial melting of metasedimentary crust under conditions of crustal thickening. The timing of emplacement suggests that crustal anatexis occurred shortly after peak collision, possibly triggered by thermal input from underplated mafic magmas or by radiogenic heating within a thickened crust. This interpretation is consistent with the presence of coeval mafic intrusions in the region, which may have provided the necessary heat source for melting. In addition, Nd–Hf isotopic characteristics of the Hai Van granitoids indicate derivation from an ancient crustal source with model ages in the Paleoproterozoic, similar to basement components recognized in the Viet-Trung domain. The occurrence of inherited Neoproterozoic zircon grains further supports the involvement of older continental materials in magma generation. These features imply that the northern Kontum massif shares a common crustal affinity with the Viet-Trung domain, reinforcing the interpretation of a continental collision between these two blocks during the Early Triassic.

Taken together, the geochronological, geochemical, and isotopic data indicate that the Hai Van granitoid complex represents a key magmatic product of the Indosinian orogeny in central Vietnam. Its emplacement records the transition from peak collision to post-collisional crustal

reworking, marked by widespread anatexis and granitoid magmatism. The results of this study therefore highlight the importance of Early Triassic magmatism in documenting the final amalgamation between the Indochina Block and the Viet-Trung continental domain, and provide new insights into the geodynamic evolution of Southeast Asia during the closure of the Palaeo-Tethys Ocean.

Conclusions

1. Petrographic and geochemical characteristics confirm an S-type affinity, reflecting magma generation by partial melting of metasedimentary crust.

2. The timing and nature of magmatism suggest emplacement during syn- to post-collisional stages of the Indosinian orogeny.

3. Tôi muốn viết: Kết quả nghiên cứu tuổi U-Pb này cùng với số liệu đã xuất bản cho imply that the Hai Van granitoid complex formed during 243–224 Ma This temporal distribution indicates that magmatism in the Hai Van complex was episodic occurring over a period of at least ~10–15 Myr.

4. The Hai Van granitoids record prolonged crustal reworking during collision/post-collision between the Indochina and Viet-Trung blocks, highlighting Triassic magmatism as a key record of Palaeo-Tethys closure in central Vietnam.

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