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

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ABSTRACT

This study investigates the U–Pb zircon ages and Hf isotopic compositions of dioritic intrusions in the Vit Thu Lu area, northern Quang Tri, which are part of the Long Dai volcanic arc. Zircon analyses yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 464.8 ± 2.2 Ma, indicating Ordovician crystallization. Hf isotopic data ($\epsilon\text{Hf}(t) = -10$ to -2) indicate a mantle-derived source enriched to varying degrees by crustal materials. Combined U–Pb, Hf isotopic, and geochemical evidence indicates that the Early Paleozoic magmatic rocks in the Vit Thu Lu area were generated in a continental arc setting, reflecting active subduction of the Proto-Tethys Ocean beneath the southern Truong Son Belt. These results provide important constraints on the timing, petrogenesis, and tectonic evolution of the Long Dai arc.

Keyword: *Vit Thu Lu diorite, U–Pb zircon geochronology, Hf isotopes (ϵHf), Proto-Tethys subduction*

1. Introduction

Magmatic rocks ranging in composition from gabbro and gabbro-diorite to diorite and granodiorite in the Vit Thu Lu area are considered part of the Long Dai volcanic arc (Tran and Vu, 2011). The Long Dai volcanic arc is a tectonic unit extending from south of the Song Ca Fault to north of the Thakhet–Da Nang Fault. According to Tran and Vu (2011), the Middle Ordovician–Middle Silurian Long Dai arc comprises predominantly clastic turbidites interbedded with minor andesite–dacite, black shales containing graptolites, and siliceous shales (chert) with radiolarians of Late Ordovician–Early Silurian age, belonging to the middle part of the Long Dai Formation. These sequences are strongly deformed into linear folds, locally overturned, and affected by thrust faults. In the northern Quang Tri area (formerly Quang Binh), intrusive rocks including diorite, granodiorite, and granite of the calc-alkaline Vit Thu Lu complex have been reported, with ages ranging from 475 to 443 Ma (Bui Minh Tam (ed.), 2010; Tran and Vu, 2011). Results from this study suggest that these magmatic rocks are associated with the main subduction stage of the Early Paleozoic Long Dai arc along the southern margin of the Truong Son Belt.

Despite the large volume of volcanic rocks within the Long Dai formation in the Quang Tri region, constraints on their timing and magma sources remain limited. This has led to ongoing debates regarding tectonic setting, magmatic evolution, and the role of Proto-Tethys subduction in the region. In particular, the relationship between intrusive and extrusive magmatic phases and the development of the Early Paleozoic Long Dai volcanic arc remains poorly understood.

This study focuses on the meta-dioritic rocks of the Vit Thu Lu area with the objectives to (i) precisely determine crystallization ages using zircon U–Pb geochronology; (ii) constrain magma sources; and (iii) discuss the tectonic setting and their implications for the evolution of the Early Paleozoic Long Dai volcanic arc along the southern margin of the Truong Son Belt.

The results provide important constraints for reconstructing the regional tectono-magmatic history and contribute to a better understanding of the closure of the Proto-Tethys Ocean.

2. Geological Setting

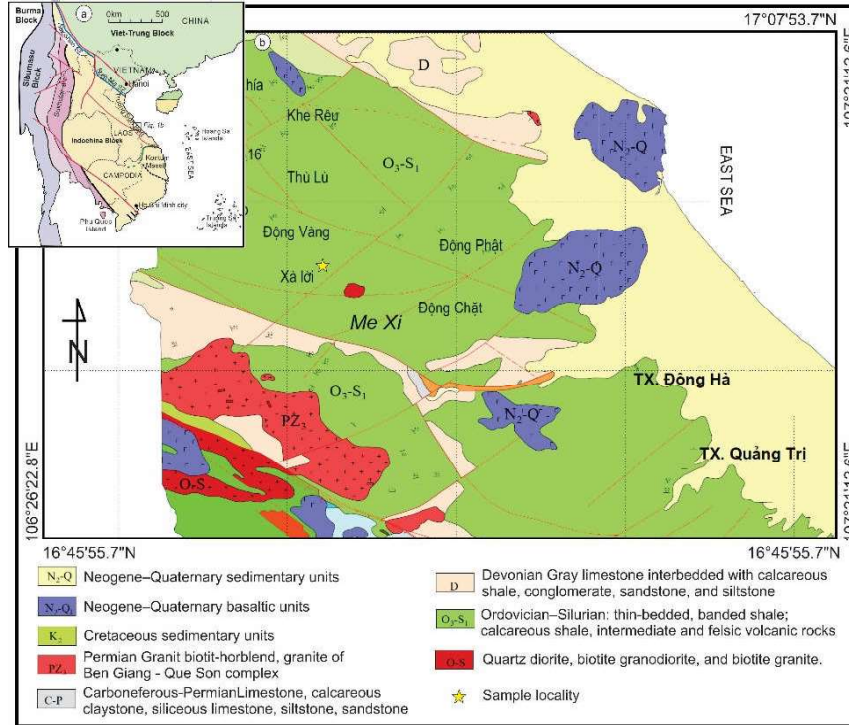


Figure 1. (a) General tectonic framework of Southeast Asia, showing the relationships among the Indochina, South China, and Sibumasu blocks, major suture zones, and large-scale fault systems; (b) Geological map of the study area showing the sample locality.

The Vit Thu Lu area is located along the southern margin of the Truong Son Belt and falls within the Early Paleozoic Long Dai volcanic arc. Structurally, the area is situated between two major fault systems, namely the Song Ca Fault to the north and the Thakhet–Da Nang Fault to the south, which are key tectonic zones that strongly controlled magmatic and metamorphic evolution in the region. The stratigraphy of the area is dominated by clastic sedimentary sequences of the Long Dai and A Vuong formation, characterized by turbiditic deposits (sandstone, siltstone, and shale) interbedded with volcanic rocks ranging in composition from andesite to dacite. In addition, siliceous rocks (chert) containing radiolarians and black shales with graptolites are present, reflecting a deep-marine depositional environment during the Late Ordovician–Early Silurian. These units are commonly strongly deformed into linear folds, locally overturned, and associated with thrust faults, indicating significant compressional tectonic events.

Magmatic activity in the region is well developed and includes both volcanic and intrusive rocks. Intrusive bodies range in composition from gabbro and diorite to granodiorite and granite, belonging to the calc-alkaline series. A representative example is the Vit Thu Lu complex, with ages of approximately 475–443 Ma. These intrusions commonly occur as small plutons or dykes cutting older sedimentary–volcanic sequences, reflecting multiple phases of magmatic activity associated with subduction and the evolution of the Long Dai volcanic arc.

Based on mineralogical and geochemical characteristics of magmatic rocks from the Long Dai Formation (including diorite, granodiorite, and biotite–amphibole granite of the Vit Thu Lu

complex), they are interpreted as products of subduction-related magmatism linked to the northwestward subduction of the Tam Ky–Phuoc Son oceanic domain. According to Tran and Vu (2011) and Tran Tuan Anh (2025), most analyzed samples, including both volcanic and intrusive rocks, belong to I-type granitoids, enriched in Rb, Sr, Zr, Ba, Th, U, and REE, but depleted in Nb and Ta. Chondrite-normalized REE patterns and primitive mantle-normalized multi-element diagrams show similarities to typical subduction-related magmatic rocks. Sr–Nd isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.7115\text{--}0.71165$; $\epsilon\text{Nd}(t) = -11.2$ to -4) indicate that the magmas were derived from a mantle source significantly enriched by crustal components. Andesite from the area yields an age of 469.6 ± 5.4 Ma, comparable to the age of gabbro–dolerite (467.2 ± 7.8 Ma) and consistent with the reported age of the Vit Thu Lu granodiorite (475 ± 5 Ma; Bui Minh Tam, ed., 2010).

Tectonically, the region records a complex evolutionary history associated with Proto-Tethys subduction and continental collision during the Early Paleozoic. The combined structural, stratigraphic, and magmatic features indicate that the Vit Thu Lu area represents part of a continental margin volcanic arc system, reflecting interactions between mantle-derived magmas and continental crust in a subduction-related setting.

In this study, diorite, granodiorite, and rhyolite samples that exhibit foliation and metamorphic overprinting were collected from the Linh Truong–Con Tien area, Quang Tri Province. The outcrops consist of relatively fresh, small blocks exposed along a trail leading to the Xa Loi gold occurrence. The rocks are grayish green in color and display weak foliation. They are medium-grained and relatively homogeneous in texture, with mineral assemblages comprising plagioclase and amphibole, and locally showing chlorite alteration. A representative diorite sample was selected for zircon U–Pb geochronology and Hf isotopic analysis.



Figure 2. Diorite outcrop from the study area: (a) field photograph showing weakly developed foliation in the diorite; (b) close-up view illustrating the medium-grained texture and mineral fabric of the rock.

3. U–Pb Zircon Geochronology and Hf Isotope Results

Zircon grains were examined in detail using cathodoluminescence (CL) imaging, and analytical spots were preferentially selected on euhedral crystals displaying typical oscillatory zoning characteristic of magmatic zircon. All analytical unjwq points plot on or very close to the concordia curve in the U–Pb concordia diagram ($^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{235}\text{U}$, 2σ), forming a tightly clustered distribution. This indicates a relatively undisturbed isotopic system with no significant Pb loss.

The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of the analyzed zircon grains yields an average age of 464.8 ± 2.2 Ma (95% confidence interval), with an MSWD of 0.28 and a probability of 0.97.

These values indicate very low data dispersion and high analytical reliability. No data points were rejected (0/9), suggesting a highly consistent and homogeneous dataset.

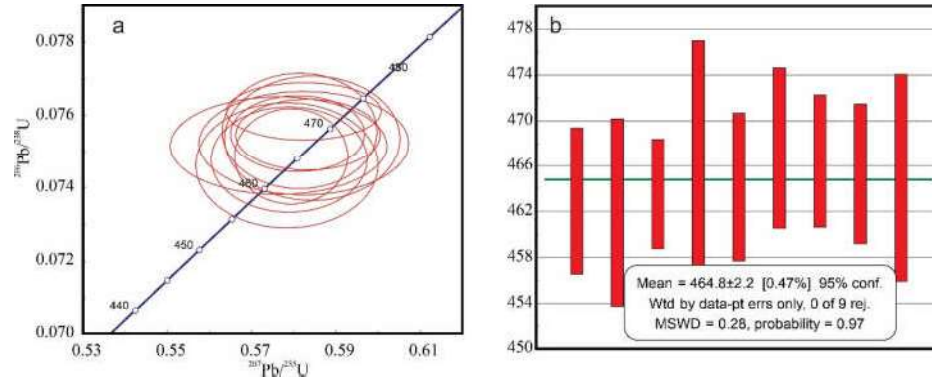


Figure 3. (a) Concordia diagram showing the U–Pb isotopic data of zircon from the studied samples. Red ellipses represent the 2σ uncertainties of individual analyses. (b) Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of the analyzed zircons.

Lu–Hf isotopic analyses were conducted on the same zircon domains used for U–Pb dating. The analyzed samples yield $\epsilon\text{Hf}(t)$ values ranging from approximately -10 to -2 ($t = 465$ Ma), which are broadly comparable to those reported for the Chu Lai granites. These results indicate that the magmas were predominantly derived from the reworking of ancient crustal materials, with only a limited contribution from the mantle (Figure 4).

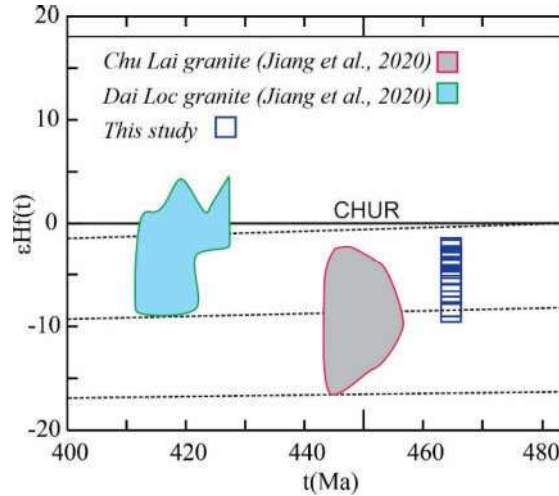


Figure 4. Variation of $\epsilon\text{Hf}(t)$ values with time (t , Ma) for diorite samples from the study area. Comparative data include S-type granitoids of the Chu Lai complex (pink) and S-type granites of the Dai Loc complex (light blue), after Jiang et al. (2020).

4. Discussion

4.1. Crystallization age of the diorite

Zircon grains analyzed in this study exhibit typical magmatic characteristics, including well-developed oscillatory zoning and homogeneous internal structures. Their Th/U ratios range from 0.32 to 1.05, all exceeding 0.1, indicating a magmatic origin (Williams and Claesson, 1987; Kinny et al., 1990). The obtained $^{206}\text{Pb}/^{238}\text{U}$ age of 464.8 ± 2.2 Ma is interpreted as the crystallization age of the diorite in the Vit Thu Lu area. This age falls within the Middle Ordovician and is consistent with previously published geochronological data from the region. Specifically, andesite yields an age of 469.6 ± 5.4 Ma, whereas gabbro–dolerite gives an age of 467.2 ± 7.8 Ma (Tran Tuan Anh, 2025). In addition, granodiorite of the Vit Thu Lu complex has been dated at 475 ± 5 Ma (Bui Minh Tam, 2010).

The similarity in ages among magmatic rocks ranging from mafic (gabbro–dolerite) through intermediate (diorite, andesite) to felsic compositions (granodiorite) suggests that they likely belong to a single magmatic system developed over a relatively short time interval (~475–465 Ma). This reflects a period of intense and sustained magmatic activity, characteristic of a subduction-related volcanic arc during the Early Paleozoic. Furthermore, the relatively tight clustering and overlap of ages within analytical uncertainties imply that magmatic evolution may have proceeded through fractional crystallization from a common parental magma, coupled with interaction between mantle-derived melts and continental crust. This interpretation is consistent with an active continental margin setting, where subduction of the Proto-Tethys Ocean supplied both material and heat to generate and evolve diverse magmatic phases.

4.2. Geological implications

The U–Pb zircon ages obtained in this study, combined with previously published data, constrain a magmatic episode at ~475–465 Ma within the Long Dai volcanic arc. When integrated with geochemical and Sr–Nd–Hf isotopic data, these results indicate that the magmatic rocks in the Vit Thu Lu area were generated within a vigorous continental arc system during the Middle Ordovician.

The similarity in ages between intrusive rocks (gabbro, diorite, granodiorite) and volcanic rocks (andesite, dacite) (Bui Minh Tam, 2010; Tran Tuan Anh, 2025) suggests the existence of a long-lived and coherent magmatic system. This reflects an active subduction regime of the Proto-Tethys Ocean beneath the southern margin of the Truong Son Belt (Tran and Vu, 2011). Negative $\epsilon_{\text{Hf}}(t)$ values (–10 to –2), together with enriched Sr–Nd isotopic signatures ($^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.7115\text{--}0.71165$; $\epsilon_{\text{Nd}}(t) = -11.2$ to –4), indicate that the magmas were not purely mantle-derived but were significantly influenced by ancient continental crustal components (Tran and Vu, 2011; Tran Tuan Anh, 2025). This is consistent with a continental arc magmatic model, in which partial melting of the lower crust is triggered by heat and material flux from the mantle wedge above the subducting slab (Pearce et al., 1984; Ngo et al., 2025).

Comparison with coeval granitoids in southern Laos (460–457 Ma), which exhibit similar geochemical and isotopic characteristics ($\epsilon_{\text{Nd}}(t) = -9.5$ to –3; $^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.70510\text{--}0.71559$), suggests the development of a regionally extensive magmatic arc system along the Truong Son Belt (Wang et al., 2020; Shang and Chen, 2022). This supports the interpretation that the Long Dai volcanic arc formed part of a continental margin arc system associated with the Early Paleozoic evolution of the Indochina Block. In addition, the occurrence of younger granitoids (~452–449 Ma) in the Dak Rong area and adjacent regions (Nguyen et al., 2024) indicates that arc magmatism may have persisted into the Late Ordovician. This likely reflects a transition from the main subduction stage to later tectonic phases, possibly related to syn-collisional or post-collisional settings, consistent with regional arc–collision evolution models in Southeast Asia (Metcalf, 2013; Jiang et al., 2020).

Overall, the combined geochronological, geochemical, and isotopic data indicate that the Vit Thu Lu area records a typical episode of continental arc magmatism during the Middle Ordovician (~475–465 Ma), directly linked to Proto-Tethys subduction. This magmatic system reflects strong interactions between mantle-derived materials and continental crust and provides important constraints on the evolution and eventual closure of the Proto-Tethys Ocean along the southern margin of the Truong Son Belt during the Early Paleozoic (Jiang et al., 2020; Metcalfe, 2013).

Conclusions

1. Zircon U–Pb dating indicates that the dioritic intrusions in Vit Thu Lu crystallized at 464.8 ± 2.2 Ma, corresponding to the middle Ordovician.
2. Hf isotopic signatures show that the magmas were primarily derived from re-melted continental crust, with minor mantle contributions.
3. The combined geochronological, isotopic, and geochemical data suggest that the Vit Thu Lu magmatic activity occurred in a continental arc setting related to subduction of the Proto-Tethys Ocean, contributing to the development of the Long Dai volcanic arc in the early Paleozoic.

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