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Zircon U-Pb age of quartz-feldspar dykes and gold mineralization characteristics at Vai Dao mine, Song Da zone, Northwest Vietnam

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Abstract: The Vai Dao mine, located in Cao Ram Commune, Luong Son District, Hoa Binh Province, is situated within the Song Da structural zone. This zone is an active intracontinental rift that existed during the Indosinian period. The region shows significant potential for gold mineralization, particularly of the gold-quartz-sulfide ore formation, in Northwest Vietnam. To determine the origin of the gold mineralization, analyses were conducted including thin section, polished section, inclusion temperature, and U-Pb zircon isotope analysis. The research results indicate that the gold mineralization in the Vai Dao mine belongs to a medium-temperature hydrothermal gold-quartz-sulfide ore formation. The typical mineral assemblage includes gold-quartz-pyrite, arsenopyrite, and gold-quartz-polymetallic sulfides. In the research area, aplite dykes and quartz-feldspar dykes are also present. U-Pb isotope age analysis on zircon minerals from quartz-feldspar dykes (sample VD3021) using the LA-ICP-MS method yielded an age range of 251-259 Ma, with an average of 255.7±4.7 Ma. Based on petrological characteristics and distribution, these magmatic formations can be classified into acid effusive, sub-effusive, and sub-intrusive rock assemblages belonging to Episode 2 of the Vien Nam Formation (P3-T1vn2). Consequently, it can be concluded that the gold-quartz-sulfide mineralization is directly related to medium-temperature hydrothermal solutions associated with the magmatism of the Vien Nam formation. This research provides a foundation for the exploration and evaluation of gold-quartz-sulfide mineralization in areas with similar geological structures.

Keywords: Intrusion, U-Pb zircon isotope, gold minerals-quartz-sulfide, Luong Son, Hoa Binh, Viet Nam

INTRODUCTION

The Vai Dao gold mine is located in the southeastern part of the Song Da structural zone, which is an intracontinental rift with a complex geological history. The Song Da zone formed during the Late Permian to Early Triassic period (P3-T1) (Dovjikov, 1965; Tri, 2009; Tam *et al*., 2010; Tri *et al*., 2016). This tectonic zone extends approximately 400 km in length and 50 to 80 km in width, bounded by the Thuan Chau and Song Da faults to the west and the Phan Si Pan zone to the east (Figure 2a).

The Song Da zone consists of a diverse array of rock types, including terrigenous sediments, terrigenous-carbonate deposits, mafic to felsic extrusive rocks, and tuffaceous sediments from the Cam Thuy (P2 ct), Yen Duyet (P2 yd), Vien Nam (T1 vn), Co Noi (T1 cn), and Dong Giao (T2a dg) formations. The extrusive rocks of the Vien Nam and Cam Thuy formations are known to host gold mineralization.

The ore mineralization at the Vai Dao mine has a hydrothermal origin and belongs to the gold-quartz-sulfide deposit type. The Song Da structural zone hosts numerous other significant mineral occurrences, including Doi Bu, Cao Ram, Lang Xen, Da Bac, Lang Ngam, Lang Ngo, and Hoa Thach.

The Vai Dao mine is located in Cao Ram Commune, Luong Son District, Hoa Binh Province, Vietnam, within the geographic coordinates of 20°47’45”-20°49’23” N and 105°29’48”-105°32’24” E, covering an area of approximately 7.5 square kilometers (Sat, 1993; Mui, 2000) (Figure 1).

The geological structure of the study area is characterized by the following key components (Figure 2a):

The Vien Nam Formation (P3-T1*vn*) is composed primarily of basaltic extrusive rocks, including aphyric

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basalt, porphyritic basalt, amygdaloidal basalt, hyalobasalt, and basalt interlayered with trachyte, rhyotrachyte, porphyritic rhyolite, felsite, and tuff. The Vien Nam Formation rocks form a prominent anticline structure at the center of the study area (Hoang & Mong, 2004; Dat, 2020), which is the primary host for gold mineralization in the form of a quartz-sulfide deposit.

The southern part of the study area is composed of terrigenous-carbonate sediments from the Co Noi Formation (T1cn). The main components include gray and brown conglomerate, gritstone, sandstone, tuffaceous siltstone, and shale interspersed with lenses of gray and green-gray shale, limestone, tuffaceous sandstone, quartz sandstone, and siltstone.

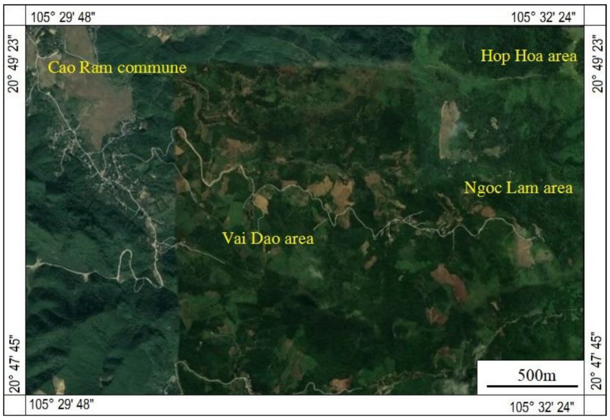

Figure 1: Study area (Source: Google Earth).

In the southwestern part of the study area, limestone from the Dong Giao Formation (T2a dg) is distributed, extending from the northwest to the southeast. The composition mainly includes black argillaceous limestone, siliceous limestone, and gray dolomitic limestone, with a thin to medium layered structure. Transitioning upwards, the limestone becomes light gray to grayish-white, with thickly bedded to massive limestone and dolomitic limestone.

Additionally, the study area contains aplite and quartz-feldspar veins ranging in size from a few centimeters to several tens of meters and extending for a few tens to a few hundreds of meters. Based on field observations, these veins are often closely associated with ore mineralization and are spatially related to the mineralized zones, making them a key focus of the research.

The gold mineralization is directly related to the Doi Bu anticline structure and the northwest-southeast fault system (Figure 2a). Within the mineralized zones, the host rocks commonly exhibit alteration features such as silicification, chloritization, sericitization, argillization, pyritization, and carbonatization (Dat, 2020; Dat *et al*., 2022).

The objective of this study is to determine the characteristics of the ore mineralization and the origin of the gold-quartz-sulfide ore at the Vai Dao mine. This

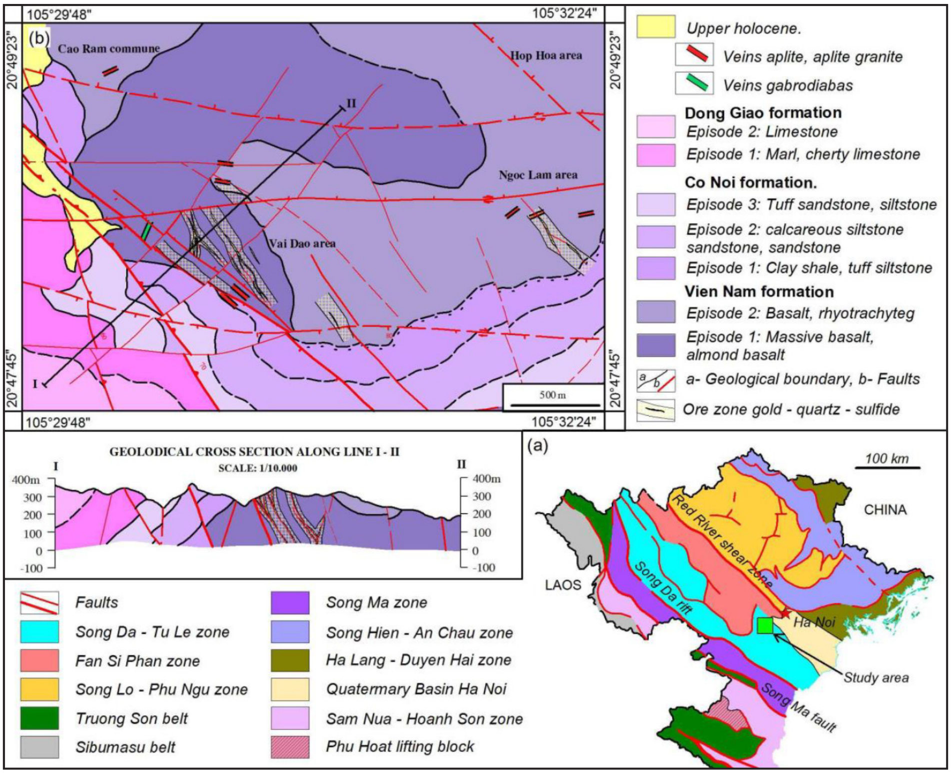

Figure 2: (a) Tectonic schema of Northern Vietnam and the study area (Tri, 2009); (b) Geological and mineral scheme of the Vai Dao mine (Hoang & Mong, 2004; Dat, 2020).

will guide further research on zonation, assessment of the denudation rate, and the potential for discovering deeply buried ore bodies in northeastern Vietnam.

MATERIALS AND METHODS

Collecting and synthesizing documents

The collected documents include geological maps at scales of 1:50,000 and 1:200,000, as well as documents on petrology, metallogeny, and mineral exploration. These documents were synthesized and analyzed to guide field investigations.

Field investigation

Field investigation routes were conducted across the entire study area. Details were surveyed according to the structural cross-section, areas with complex structures, expressions of ore minerals, and changes in petrographic composition. Detailed geological research at a scale of 1:10,000 identified geological boundaries, positions of magmatic intrusive rocks, and connections between ore bodies and ore zones. Samples were also taken for analysis of polished sections, thin sections, geochemistry, inclusions, and artificial placers to study the characteristics and origin of ore minerals.

U-Pb zircon isotope analysis by LA-ICP-MS

This technique enables us to determine the formation age of rock (Miller *et al*., 2003; Watson & Harrison, 2005; Hieu *et al*., 2015). The analysis was performed on a quartz-feldspar vein sample taken from the VD.3021 outcrop, located at geographic coordinates 20°48'15" N and 105°30'58" E (Figure 4). Zircon grains were separated using an artificial placer method and a stereomicroscope (ZEISS-Stemi 2000-C) at the Mineral Research Department, Vietnam Institute of Geosciences and Mineral Resources. The polished zircon samples were analyzed for zonal structure characteristics by scanning electron microscopy (SEM). LA-ICP-MS U-Pb analysis was performed within a 32 µm diameter, typically selected at the crystal center and at the overlap edge of pure, uncracked, inclusion-free zircon grains. This analysis was performed at the Isotope Geochemistry Laboratory, Hiroshima University, Japan.

Petrographic analysis

This method was performed to determine the mineral composition, structure, and textures of the magmatic rocks associated with the mineralization zone. Samples were taken from the VD3021 outcrop. After processing, the thin sections were analyzed using an optical polarizing microscope, Zeiss AXIOLAB, at the Department of Lithology and Isotope Geology, Vietnam Institute of Geosciences and Mineral Resources.

Mineral facies analysis

This method was performed to study the mineral composition, structure, textures, ore relationships, formation order, and ore mineral associations. Gold ore samples were collected from ore zones and ore bodies, in order from top to bottom and according to mining depth (Figure 3). Polished sections were prepared and analyzed using an AXIOKOP 40 reflectance polarized microscope at the Technology Center for Geology and Minerals, Vietnam Institute of Geosciences and Mineral Resources.

Inclusion assimilation temperature analysis

Inclusion samples were taken from hydrothermal quartz veins containing ore minerals and associated with ore formation processes. The samples were collected from top to bottom according to the mining levels in the mine tunnel (Figure 4). Inclusion temperature analysis was performed using a Linkam TMS 600 system at the Department of Lithology and Isotope Geology, Vietnam Institute of Geosciences and Mineral Resources.

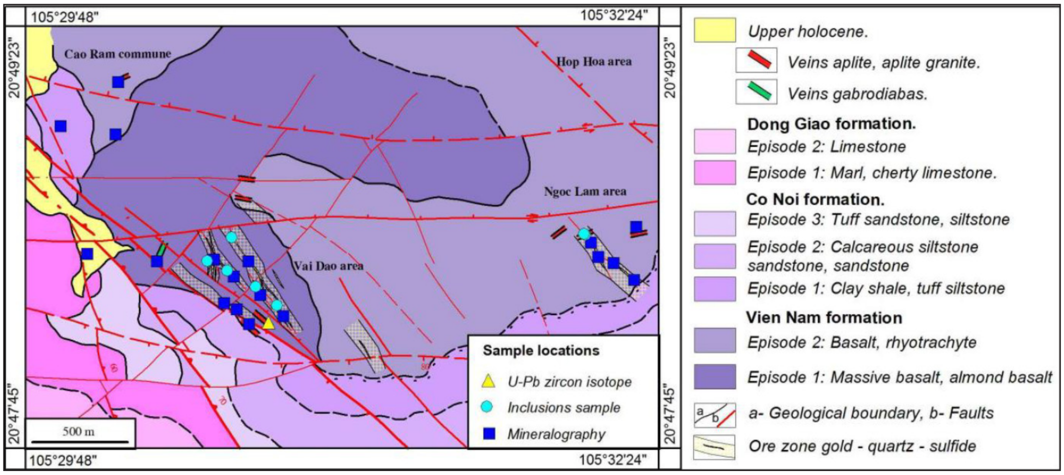

Figure 3: Sample locations.

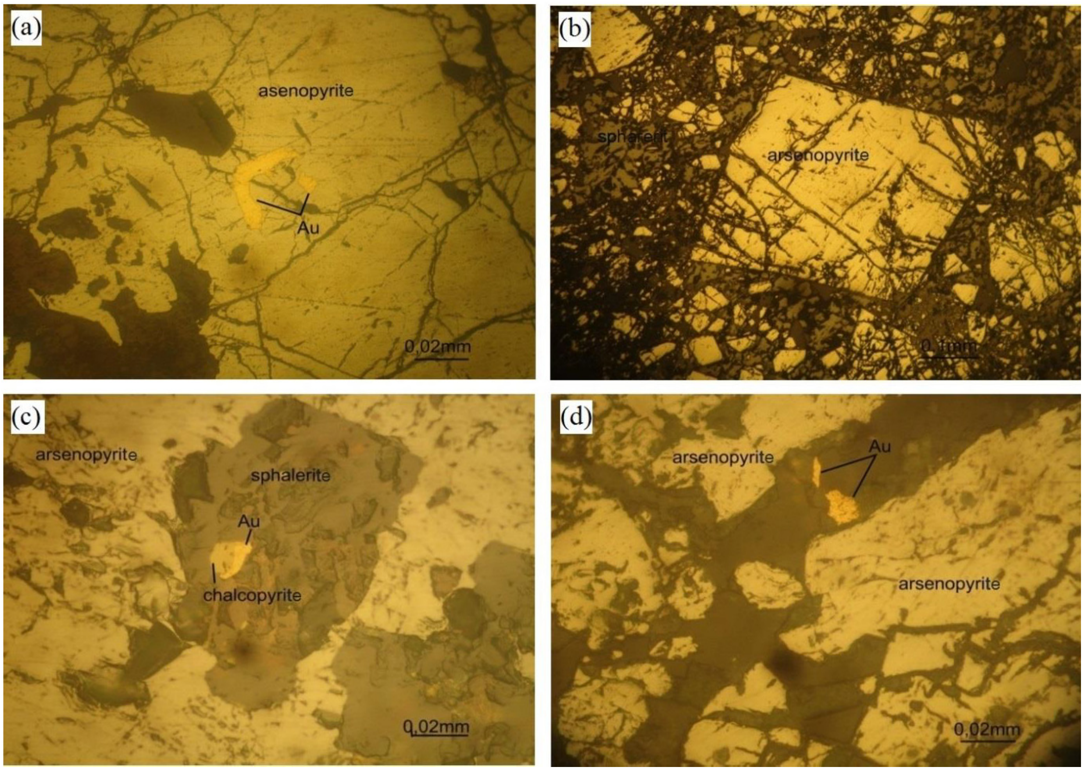

Figure 4: Mineralographic images of polished analysis under the reflected light. (a) Two gold grains from sample VD.118/13, one grain is relatively isometric, size 0.02mm, and one grain is elongated tubular, size 0.02x0.15mm; (b) Arsenopyrite panidiomorphic granulated with sphalerite plate form automorphic and polymorphic from ample VD.118/24, (c) Small gold (0.01x0.02mm) and chalcopyrite are found in sample VD.118/21. They are located within sphalerite, sphalerite is located within arsenopyrite; (d) Native gold associated with arsenopyrite from sampleVD.118/24.

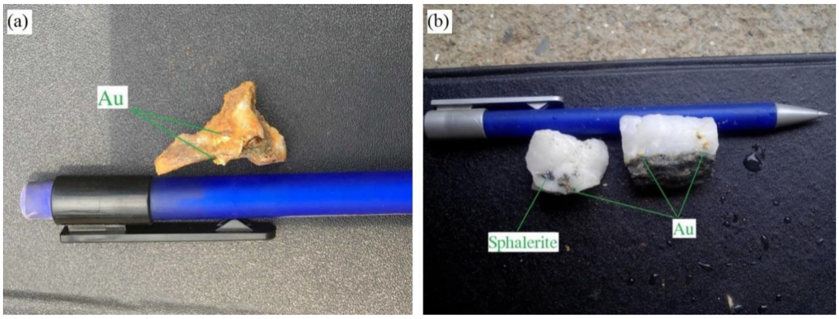

Figure 5: (a) Native gold and a symbiotic combination of quartz-arsenopyrite and pyrite, representing the first stage of mineral formation, and (b) Gold-quartz-polymetallic sulfide ore, characteristic of the second stage of mineral formation.

RESULTS

Characteristics of ore minerals

Gold ore minerals were found filling the fractures and faults of the northwest-southeast system within the extrusive rocks of the Vien Nam Formation. After separating from magmatic activity, the hydrothermal solution moves along the channels of these fault systems and, upon encountering favorable conditions, accumulates and deposits into ore bodies and ore zones. As a result, the ore bodies are primarily in the form of veins and lenses. The ore structures are dense, nested, disseminated, pseudo-layered, crushed, and brecciated. The ore textures are panidiomorphic, hypidiomorphic, xenomorphic, corroded, and skeletal (Binh, 1997; Dat, 2020) (Figure 4a, b).

The primary ore mineral assemblage at the Vai Dao deposit is dominated by pyrite, arsenopyrite, galena, native gold, and lesser amounts of chalcopyrite and sphalerite (Figure 5a-b). Secondary alteration minerals include limonite, goethite, and leucoxene.

The gold mineralization has two main ore types: (1) quartz-pyrite-arsenopyrite-hosted gold, and (2) gold associated with quartz-polymetallic sulfide. Gold grains are usually small in size from 0.01-0.2 mm, few grains are larger than 1 mm. Gold grains are found in quartz veins, in altered extrusive host rocks, and intimately intergrown with pyrite and arsenopyrite.

The morphology of the gold grains is highly variable, ranging from fine dust-like particles to distorted, elongated forms. In certain areas, gold is concentrated in clusters surrounding quartz grains, with the gold being emplaced along fractures cutting through the quartz.

Based on the previous publication of Dat (2020), the mineral paragenesis of the gold mineralization can be divided into four distinct stages:

Pre-ore hydrothermal stage: This stage is characterized by the formation of thick quartz veins accompanied by widespread hydrothermal alteration, including silicification, chloritization, and sericitization. There is no mineralization in this stage.

Ore-forming stage 1: This is the primary stage of sulfide mineralization, with a typical mineral assemblage of quartz-arsenopyrite-pyrite-gold. The main ore minerals include arsenopyrite, pyrite, native gold. The secondary minerals are chalcopyrite, sphalerite, pyrrhotite, and very little magnetite, hematite. In addition, there are quartz veins. Typical hydrothermal alteration includes quartzitization, chloritization, sericitization, propylitization, and anglicization. The temperature of the hydrothermal fluids during this stage is 260-398°C.

Ore-forming stage 2: This stage involves the formation of a quartz-pyrite-arsenopyrite-polymetallic sulfide-gold mineral assemblage. The ore minerals are predominantly pyrite, arsenopyrite, gold, and lesser amounts of chalcopyrite, sphalerite, and galena. Non-ore minerals include quartz, sericite, chlorite, and epidote. Fine grained gold is disseminated in arsenopyrite, pyrite, limonite, and in quartz veins. Hydrothermal alteration during this stage includes sericitization, beresitization, quartzization, and sulfidization. The ore formation temperature ranged from 195-310°C.

Post-ore hydrothermal stage: This final stage is characterized by the formation of quartz veins, thick carbonate-quartz veins, chloritization, and quartzization. This stage has little to no associated ore mineralization.

Characteristics of inclusion assimilation temperatures

The analysis results show that the inclusions in quartz associated with gold mineralization are mainly liquid-gas inclusions and gas-liquid inclusions (Table 1; Figures 6a,b).

Liquid-gas inclusions are prevalent and found in all analyzed samples with oval, multiangular, or elongated

Table 1: Summary of the inclusion analysis results in quartz and gold ore minerals from the Vai Dao ore deposit.

Samples	Liquid-gas inclusion						Gas-liquid inclusion					
	Shape	Size (μm)	Components of phases (%)		Density (bt/mm^2)	Assimilation temperature (°C)	Shape	Size (μm)	Components of phases (%)		Density (bt/mm^2)	Assimilation temperature (°C)
			Liquid	Gas					Liquid	Gas		
VD.102/3	Oval, tubu-lar	1-3	80-90	10-20	>100	195-240						
VD.118/2	Oval, tubu-lar	3-8	80-90	10-20	50-100	205-298	round-ed, oval	5-8	20-30	70-80	<50	345-398
VD.3018/2	Oval, tubu-lar	3-8	80-90	10-20	50-100	205-310	round-ed, oval	5-8	20-30	70-80	<50	345-398
VD.3019	Oval, tubu-lar	3-8	80-90	10-20	50-100	210-245	round-ed, oval	5-8	20-30	70-80	<50	260-325
VD.3020/1	Oval, tubu-lar	2-8	80-90	10-20	<50	205-265	round-ed, oval	5-8	20-30	70-80	<50	301-350
VD.3024	Oval, tubu-lar	2-4	80-90	10-20	>100	205-275	round-ed, oval	5-8	20-30	70-80	<50	305-385
VD.3025/1	Oval, tubu-lar	2-5	80-90	10-20	>100	220-286	round-ed, oval	5-8	20-30	70-80	<50	310-365

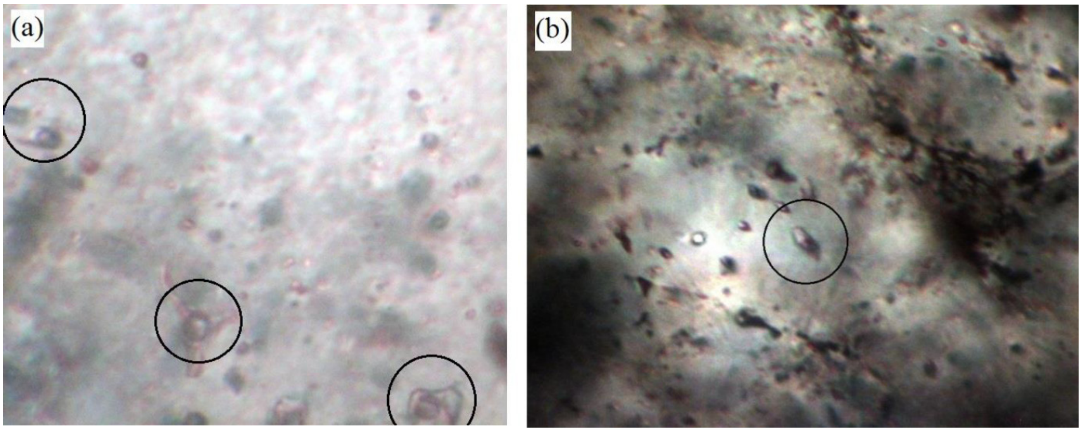

Figure 6: Image of the inclusions assimilation temperature analysis. (a) Gas-liquid inclusion in quartz mineral (VD.3018/2), (b) Liquid-gas inclusion in quartz mineral (VD.3019).

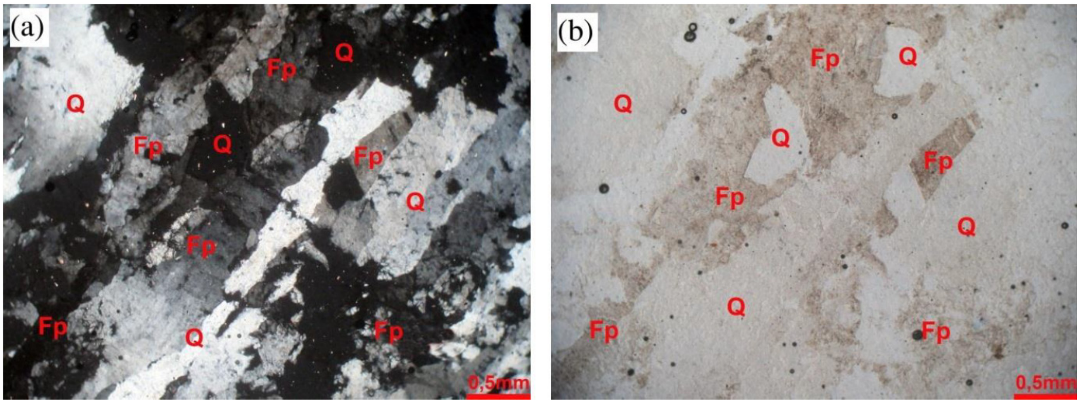

Figure 7: Photomicrograph of the quartz-felspar vein (sample VD3021) under (a) - Nikon (+), (b) - Nikon (-). Q - Quartz; Fp - Felspar.

tubular shapes. The liquid component accounts for a large proportion of 80-90%, and the size varies from 1-8 μm. The inclusion assimilation temperature ranges from 195-310°C.

Gas-liquid inclusions are less common, mostly oval or round in shape. The inclusion size is relatively stable, ranging from 5-8 μm. The gas-liquid composition is also less variable than that of fluid-gas inclusions, the gas phase usually accounts for about 70-80%. The inclusion assimilation temperature varies from 260-398°C.

This result shows that the formation temperature of quartz is from medium-high to medium-low. The temperature of quartz formation in the early ore formation stage is in the range of 260-398°C, with an average of 329°C, and in the late ore formation stage is in the range of 195-310°C, with an average of 252°C (Dat, 2020) (Table 1).

U-Pb zircon isotope age of the quartz-feldspar vein

Petrological characteristics

U-PB iso age analysis was performed on quartz-feldspar vein sample (VD3021). Visually, the sample VD3021 is a gray-white, microporphyritic structure can be seen with a few small phenocrysts of 1-2mm, the rock is strongly altered so it looks quite similar to felsite. Thin section analysis under a polarizing light microscope shows that the minerals are mainly composed of quartz (78-89%) and potassium feldspar (20-25%) (Figure 7). The feldspar has elongated comb-like texture, with the grains oriented perpendicular to the vein. The feldspar is intergrown with quartz, forming aggregated grain clusters. The sample surface appears to be stained brown, likely due to clay alteration.

Cathodoluminescence image (CL) using scanning electron microscopy (SEM)

The scanning electron microscopy cathodoluminescence (SEM-CL) image of the zircon grains from the quartz-feldspar vein sample (VD3021) reveals that the zircon grains exhibit a range of morphologies, including: (1) Predominantly panidiomorphic granular (euhedral) zircon grains; and (2) some have automorphic granular (subhedral) and rounded (anhedral) zircon grains. The grain sizes range from 40-100 μm, with euhedral grains being larger (>60 μm) and displaying more distinct zonal structures under SEM-CL.

Together with the zircon U-Pb age data for each zircon grain displayed in Figure 8, the zircon structure analysis indicates that the zircons in the Vai Dao ore-bearing magmatic rocks have a complex genesis, comprising two distinct populations: (1) Euhedral zircon grains: This population grew directly from the magma during the cooling and solidification of the quartz-feldspar vein, crystallizing under the specific physicochemical conditions of the magmatic hydrothermal system. (2) Subhedral to anhedral zircon grains: These zircons likely represent inherited or xenocrystic grains that were entrained from the country rocks during the emplacement of the magmatic system. They may have originated from older igneous or metamorphic sources and were incorporated into the magma.

The presence of these two zircon populations, as evidenced by the variations in their morphologies, internal structures, and potential age differences, suggests a multi-stage history for the Vai Dao ore-bearing magmatic rocks. The inherited, xenocrystic zircons provide insights into the nature of the crustal sources that contributed to the magma genesis, while the magmatic zircons record the timing and conditions of the ore-forming hydrothermal event.

Zircon U-Pb geochronology

Sample VD3021 was selected for U-Pb isotope analysis. The sample represents feldspar-quartz intrusions associated with ore mineralization and is relatively fresh and unaltered. A total of 19 zircon grains were analyzed; the results are presented in Table 2, and the Concordia plots are displayed in Figure 9.

Figure 8: Cathodoluminescence images of the zircon grains and the zircon U-Pb age of each grain from the quartz-feldspar vein sample (VD3021).

Table 2: Analytical results of U-Pb zircon isotope age sample VD3021.

Sample, no	Corrected Ratios						Corrected Ages (Ma)					
	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
VD3021-1	x	x	x	x	x	x	x	x	x	x	x	x
VD3021-2	0.0516	0.0026	0.291	0.0143	0.0409	0.0008	266	118	259	11	259	5
VD3021-3	0.0705	0.001	1.5282	0.0249	0.1572	0.0021	943	29	942	10	941	12
VD3021-4	0.0708	0.001	1.5436	0.0252	0.158	0.0022	953	29	948	10	946	12
VD3021-5	0.0662	0.001	0.7712	0.0127	0.0845	0.0011	813	31	580	7	523	7
VD3021-6	0.0518	0.0009	0.292	0.0058	0.0409	0.0006	276	43	260	5	258	4
VD3021-8	0.0527	0.002	0.356	0.0136	0.049	0.0009	318	88	309	10	308	5
VD3021-9	0.1422	0.0049	5.8895	0.183	0.3005	0.0045	2254	61	1960	27	1694	22
VD3021-10	0.0573	0.0008	0.6325	0.0104	0.0801	0.0011	503	32	498	6	496	7
VD3021-11	0.0749	0.0013	1.8311	0.0345	0.1773	0.0026	1066	34	1057	12	1052	14
VD3021-12	0.0686	0.0009	1.3874	0.0216	0.1467	0.002	886	28	884	9	883	11
VD3021-13	0.0779	0.0011	1.7277	0.027	0.1608	0.0021	1145	28	1019	10	961	12
VD3021-14	0.0694	0.0009	1.36	0.0211	0.1422	0.002	910	26	872	9	857	11
VD3021-15	0.0514	0.0025	0.2905	0.0138	0.041	0.0008	260	114	259	11	259	5
VD3021-16	0.0517	0.0024	0.2862	0.0214	0.0402	0.0014	272	101	256	17	254	9
VD3021-17	0.0531	0.0011	0.291	0.0128	0.0398	0.0013	332	45	259	10	251	8
VD3021-18	0.0635	0.0017	0.3481	0.0178	0.0398	0.0013	726	53	303	13	251	8
VD3021-19	0.0536	0.0017	0.293	0.0166	0.0397	0.0013	353	66	261	13	251	8
VD3021-20	0.0515	0.0019	0.2846	0.018	0.0401	0.0013	265	80	254	14	253	8

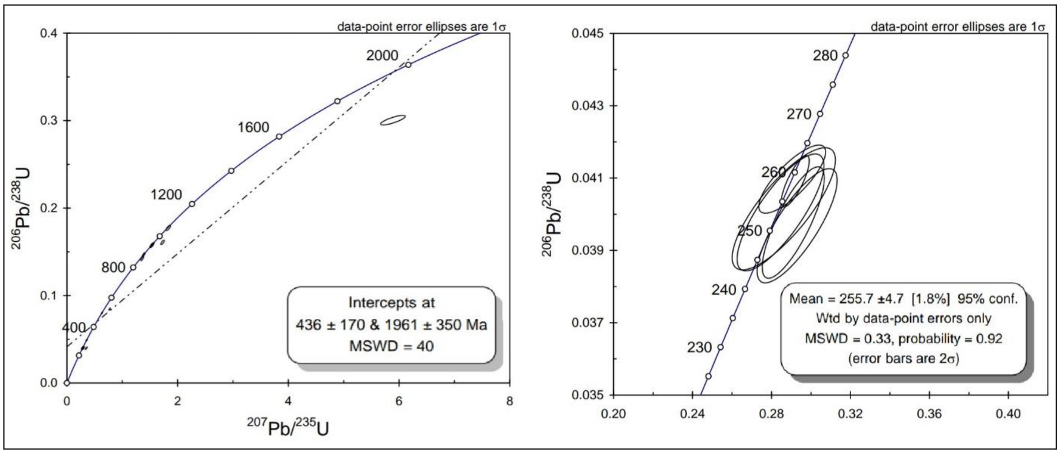

Figure 9: Concordia plots of the zircon U/Pb data from the quartz-feldspar rock sample (VD3021).

The U-Pb zircon isotope age analysis reveals a range of ages from 2254-250 Ma, with a concentration mainly in the range of 251-259 Ma (8 analysis spots). Eight euhedral zircons have a weighted mean 206Pb/238U age of 255.7±4.7 Ma, representing the crystallization age of the intrusive quartz-feldspar rocks in the Vai Dao deposit (Figure 9). Ten other inherited zircons yielded U-Pb ages ranging from 2254-308 Ma, representing the age of remnant components present in Earth's crust.

Inherited U-Pb ages and their relation to the recycling of the regional crust

The U-Pb zircon isotope analysis, combined with a cathodoluminescence study of the internal structure of the zircon grains (Figure 9), revealed remnant components ranging from 2254-308 Ma. These can be divided into Proterozoic (2500-635 Ma) and Cambrian (529-485 Ma) periods. These inherited zircons likely represent older crustal materials that were incorporated into the magma during its emplacement. It is plausible that these older zircon grains were derived from elsewhere and deposited during the Cambrian to Proterozoic periods. This suggests the presence of crustal components ranging from 308-2254 Ma in the study area and the incorporation of materials from sources such as the South China, Simao, and Sibumasu Blocks (Hoa *et al*., 2005, Hieu *et al*., 2015; Hieu *et al*., 2016).

DISCUSSIONS

Field observations indicate that the intrusive dykes are emplaced within fractures and faults in the extrusive rocks of the Vien Nam Formation. The U-Pb zircon isotope age analysis yielded an age of 255.7 ± 4.7 Ma, corresponding to the Late Permian-Early Triassic period. These results are consistent with the age of extrusive magmatism in Episode 2 of the Vien Nam Formation (Hoanh & Mong, 2004; Thanh & Khuc, 2005). Therefore, these intrusive formations can be classified as part of the extrusive, subvolcanic, and dyke associations of Episode 2 of the Vien Nam Formation (P3-T1vn2).

The origin of the gold mineralization, associated with quartz-sulfide assemblages at the Vai Dao mine, has been a subject of debate. Several perspectives have been proposed:

- In the extrusive rock-dominated areas of Vien Nam, Doi Bu, and Ba Vi, the gold mineralization is directly related to the formation of extrusive acid rocks and post-extrusive hydrothermal activity (Thang *et al*., 1995).
- The quartz-sulfide-gold mineralization is spatially associated with extrusive dykes in Ba Vi and Vien Nam and is genetically linked to the extrusive and subvolcanic acid to intermediate magmatic activity (Bat, 1998).
- The gold mineralization is related to the intrusion of Late Triassic acid magmatism of the Kim Boi complex (γT3 kb) at depth (Thoang, 1997).
- The gold mineralization in Ba Vi-Vien Nam and Cao Ram-Doi Bu is associated with medium-temperature (240-340°C) hydrothermal activity, although the origin of the hydrothermal fluids is not discussed (Mui, 2000).
- The copper-gold mineralization in the Vai Dao mine is not directly related to the igneous rocks of the Vien Nam Formation. Instead, it is of hydrothermal origin, potentially associated with a deeply buried magmatic intrusion. The isotope age of an extrusive rock in the Doi Bu area is 283 ± 20 Ma, while the ore formation age is 123-155 Ma, suggesting a time interval of over 110 Ma, which makes it difficult to relate them to the same magmatic source (Sat, 1993).

Based on existing research and the findings of this study, it can be concluded that the gold-quartz-sulfide mineralization at the Vai Dao mine is of hydrothermal, extrusive origin. The mineral assemblage is characterized by gold-quartz-pyrite, arsenopyrite, and gold-quartz-polymetallic sulfide. The fluid inclusion data indicate a medium-temperature hydrothermal origin, with homogenization temperatures ranging from 195-310°C for liquid-gas inclusions and 260-398°C for gas-liquid inclusions.

The origin of the hydrothermal fluids responsible for ore formation at the Vai Dao mine can be directly related to the emplacement of aplitic, quartz-feldspar, and feldspar dykes, as well as the extrusive activity of Episode 2 of the Vien Nam Formation (P3-T1vn2). Studies show that the gold mineralization is spatially associated with the extrusive formations of the Vien Nam Formation and is closely related to post-extrusive hydrothermal activity. This is evidenced by the close spatial relationship between the mineralization zones and the subvolcanic rhyolitic to trachytic dykes. The research results indicate that the gold content is higher in rhyotrachytic and alkaline feldspar trachytic rocks compared to basaltic rocks. Additionally, the gold-bearing quartz-sulfide veins are hosted within basalt and tuff-agglomerate rocks, but no ore was detected in the terrigenous sedimentary rocks.

These research findings are consistent with previous studies (Luong *et al*., 1992; Thang *et al*., 1995; Bat, 1998) and are acceptable, as the Late Permian-Early Triassic (P3-T1) period is recognized as one of the main stages of gold mineralization in Northern Vietnam (Hoa *et al.*, 2005, 2008; Hoa, 2007, 2010).

CONCLUSIONS

The U-Pb zircon geochronology, determined by the LA-ICP-MS method, reveals that the intrusive quartz-feldspar dykes at the Vai Dao Gold deposit have a crystallization age range of 259 Ma to 251 Ma, with an average age of 255.7 ± 4.7 Ma. This age corresponds to the Late Permian-Early Triassic (P3-T1) periods, allowing the classification of these intrusive formations as part of the subvolcanic and extrusive rock associations of Episode 2 of the Vien Nam Formation (P3-T1vn2).

The gold mineralization, characterized by quartz and sulfide assemblages, is of medium-temperature hydrothermal origin, with temperatures ranging from 195-398°C. The mineral paragenesis includes gold-quartz-pyrite, arsenopyrite, and gold-quartz-polymetallic sulfide. This hydrothermal mineralization is likely related to the subvolcanic and dyke formations of Episode 2 of the Vien Nam Formation, which developed within the Song Da Intracontinental rift.

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AUTHORS CONTRIBUTION

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by NVD, LCT, THS, TDT. The first draft of the manuscript was written by NVD, LCT, and all authors commented on previous versions of the manuscript. Supervision, conceptualization, writing–review and editing by LCT. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors affirm that there are no conflicts of interest in relation to this research, nor are there any personal relationships that could be perceived as potentially exerting influence on the findings presented in this paper.

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