

Mineralisation styles and sulfur isotopes of the Kon Ra Cu-Au deposits, Kon Tum Massif: Implication for deep mineralisation potential

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Abstract: The Kon Ra Cu-Au deposit is located in the central Kon Tum Massif, a region renowned for its geological complexity and metallogenic significance in Southeast Asia. This deposit is a notable example of skarn mineralisation, hosted within the Neoproterozoic Kham Duc sequence of metamorphic rocks, including pyroxenite, amphibolite and metacarbonates, which have been intruded by Ordovician-Silurian and Permian-Triassic magmatic events. Detailed core logging and field investigations have identified multi-stage mineralisation, including pre-ore, syn-ore, and post-ore phases. Pre-ore metasomatism is characterised by skarn formation dominated by pyroxene, amphibole, and magnetite, with minimal garnet, suggesting a distal setting relative to intrusion contacts. During the syn-ore stage, retrograde metasomatism facilitated hydrothermal fluid activity, resulting in the precipitation of chalcopyrite, pyrite, and pyrrhotite alongside altered minerals such as quartz, actinolite, epidote, chlorite, sericite and carbonate. The common ore textures include disseminated, patchy and stockwork forms with localized fabric-aligned magnetite corresponding to the S_1 foliation of the host rocks. The $\delta^{34}\text{S}$ values of the ore-bearing stages ranging from -7.3‰ to 0.31‰, indicate a predominantly magmatic sulfur source with possible minor contribution from sedimentary host rocks. While Re-Os molybdenite dating is still pending, the timing of mineralisation is assumed by a ~3 m-wide hornblende-bearing granite dyke associated with skarn alteration. This dyke is interpreted to be correlated with the Ordovician-Silurian Dien Binh or the younger Permian-Early Triassic Ben Giang-Que Son intrusion in the vicinity.

Keywords: Kon Ra, Kon Tum Massif, Cu-Au mineralisation, sulfur isotope, U-Pb apatite, Ordovician-Silurian

INTRODUCTION

The Kon Tum Massif (KTM) in central Vietnam is an important structural terrane that reveals the prolonged and complex geological evolution of the Indochina Block (Figure 1a). The tectonic history of the KTM encompasses a multi-phase evolution starting with the assembly of microcontinental fragments during the convergence of the Proto-Tethys Ocean (Li *et al.*, 2018) and the geological evolution of the Palaeozoic and Mesozoic orogeny (Lepvrier *et al.*, 2004; Faure *et al.*, 2018). The geochemical, geochronological, and isotopic data of the high-grade metamorphic and magmatic complexes indicate active crustal dynamics such as crustal melting, mantle-crust interactions, and metamorphism during such episodes (Owada *et al.*, 2007; Osanai *et al.*, 2008; Nakano *et al.*, 2021). These models have suggested favourable

environments for various styles of mineralisation, especially along shear zones such as the Tam Ky-Phuoc Son zone that channelled ore-forming fluids as demonstrated by Manaka (2014), Tran *et al.* (2014), and Khin Zaw *et al.* (2014).

In the KTM there are dozens of metallic deposits and occurrences of Au, Cu, Cu-Au, Mo, and Pb-Zn, including the Kon Ra Cu-Au deposits which are considered a significant discovery by government geologists as well as the most important evidence of Cu-Au metallogeny in the region. These deposits have attracted the attention of geologists as they provide an excellent opportunity to understand regional metallogeny. So far, the deposits have not been well studied. The mineralisation characteristics, ore-forming processes, spatial distribution, alteration zoning, and potential for deeper mineralisation in the Kon Ra Cu-Au deposits remain

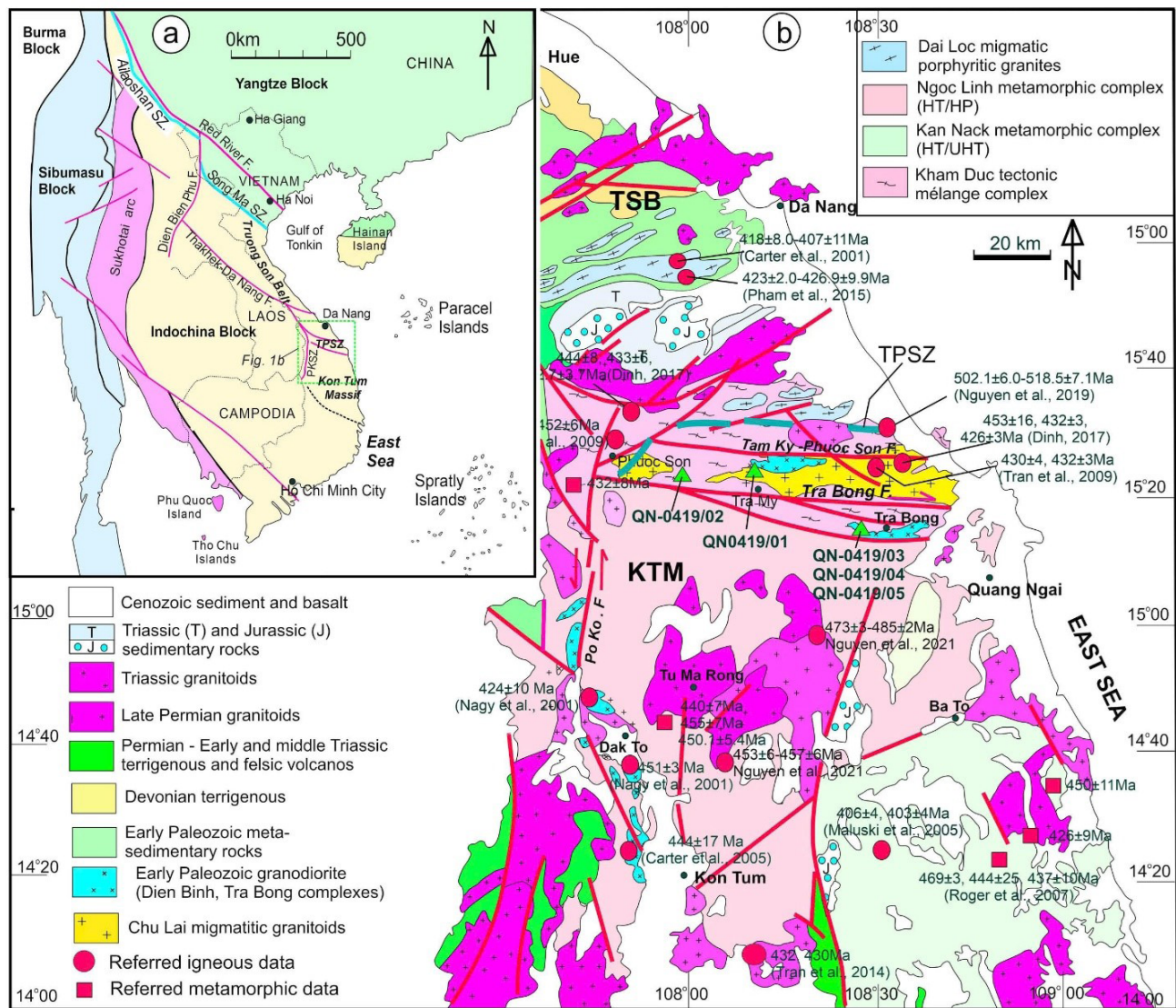


Figure 1: (a) Simplified tectonic features of Southeast Asia (after Metcalfe, 2013) and location of Kon Tum Massif (KTM), Tam Ky-Phuoc Son Suture Zone (TKPS) and Truong Son Belt (TSB). (b) Simplified geological map of the TSB and KTM across the TKTP (Modified after Phan, 2009). Referenced ages of igneous and metamorphic rocks are from Nagy *et al.*, 2001; Carter *et al.*, 2001; Maluski *et al.*, 2005; Roger *et al.*, 2007; Usuki *et al.*, 2009; Nakano *et al.*, 2013; Pham *et al.*, 2015; Dinh, 2017; Gardner *et al.*, 2017; Nguyen *et al.*, 2019; Nguyen *et al.*, 2021; Ngo *et al.*, 2022; Nguyen *et al.*, 2024.

poorly understood. In this study, we present the results of field investigations, detailed core logging, petrographic and sulfur isotopic analysis with the aim of (1) characterizing the geology and mineralisation styles of the Kon Ra Cu-Au deposits, and (2) constraining the sources of ore formation. The findings of this study will contribute to the development of an initial model for mineralisation, which is essential for future assessments of mineralisation at depth in the area.

GEOLOGICAL SETTING

Regional geology

The KTM exhibits a prolonged geological history involving the block and its accretion with other terranes. The KTM contains a variety of igneous, metamorphic,

and sedimentary rocks from the Precambrian to Triassic, characterised by distinct tectonic processes. These rocks are strongly influenced by two major tectonic events, including the Caledonian (Early Palaeozoic) and Indosinian (Late Palaeozoic – Early Mesozoic) orogenies (e.g., Nagy *et al.*, 2001; Roger *et al.*, 2007). The Caledonian orogenic events that occurred during ~520-450 Ma were driven by bilateral subduction between the Truong Son Belt (TSB) and the KTM, culminating in a collision marked by the Tam Ky-Phuoc Son Suture Zone (TPSZ) during ~450-430 Ma (Dung *et al.*, 2024). Magmatic activity during this event is presented by mafic to felsic rocks aged ~488-457 Ma west of the Po Ko Fault Zone (Nguyen *et al.*, 2024); diorite to granite complexes aged ~485-473 Ma (Pham *et*

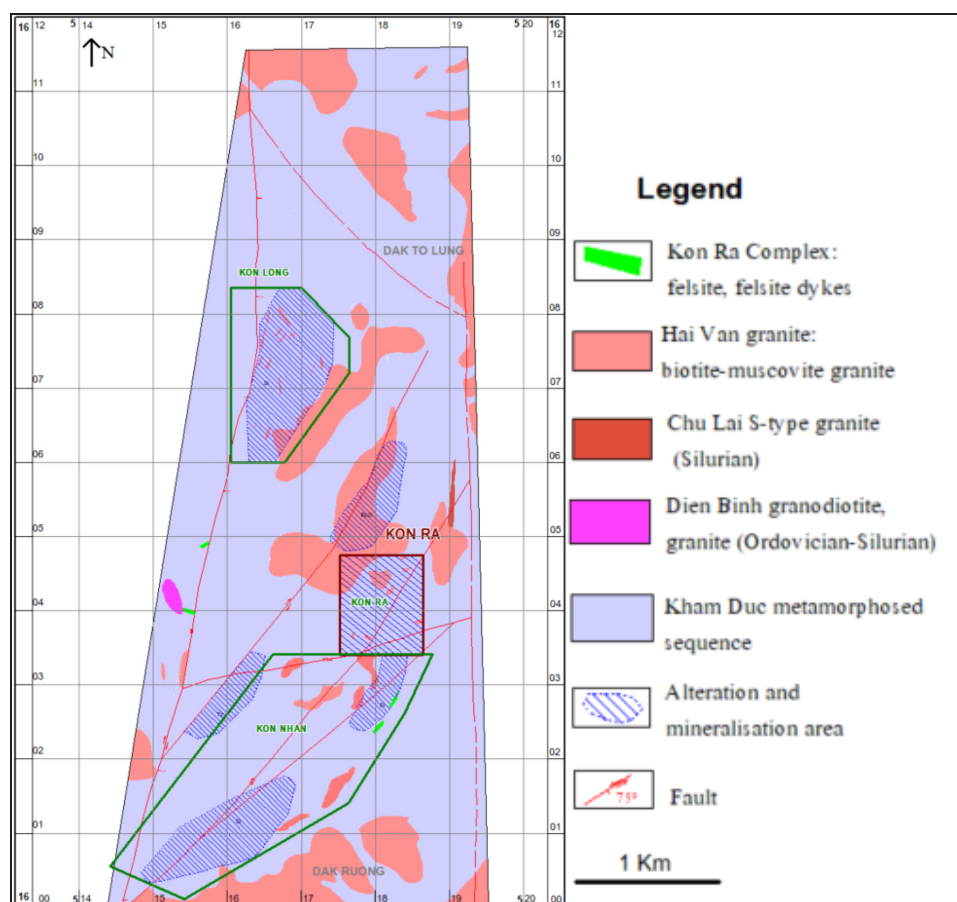


Figure 2: Simplified geological map of the Kon Ra area. The location of this area is shown in Figure 1.

al., 2015; Nguyen *et al.*, 2021), ~468 Ma (Roger *et al.*, 2007), and ~457-451 Ma (Nagy *et al.*, 2001; Nguyen *et al.*, 2021), primarily observed south of the TPSZ and east of the Po Ko Fault Zone. In the TSB, the pre-collisional I-type granite aged ~452 Ma located north of the TPSZ (Dung *et al.*, 2024) is also an indicator of this event. The collisional episode between the KTM and TSB (~450-430 Ma) is evidenced by ~455-445 Ma syn-collisional Chu Lai Complex north of the TPSZ (Jiang *et al.*, 2020; Minh *et al.*, 2020). In northeastern Vietnam, the ~428 Ma Song Chay S-type granites (Roger *et al.*, 2000) may also be related to this tectonic convergence. The collision resulted in regional metamorphism at greenschist facies, with localized zones of higher-grade metamorphism (Tran Van Tri *et al.*, 2009).

The post-collisional phase between the TSB and KTM is evidenced by intermediate to granitic intrusions of the Dai Loc Complex, dated ~415-423 Ma to the north of the TPSZ (Jiang *et al.*, 2020; Nguyen *et al.*, 2021) and early Palaeozoic and Devonian sedimentary rocks in the region (Duong *et al.*, 1996). Further, scattered Ordovician-Silurian (O-S) igneous rocks have been identified south of the TSB, characterised by their lithological associations and spatial relationships with adjacent units (Duong *et al.*, 1996).

The Indosinian orogeny (Permian-Early Triassic) was initiated by subduction between the South China and

Indochina blocks in the Early Permian and culminated in a collision during the Early Triassic along the Song Ma Suture Zone (Tran *et al.*, 2014; Dung *et al.*, 2024). Intermediate to I-type granites (~290-245 Ma) are widespread across the TSB and KTM, including ~270-260 Ma magmatic rocks of the Dien Bien Complex in the southern Song Ma Suture Zone and the central TSB, west of Nghe An Province (Shi *et al.*, 2015; Hieu *et al.*, 2017). The collisional phase is marked by S-type granite emplacement and associated metamorphism, with greenschist to amphibolite facies dominant in the TSB (Carter *et al.*, 2001; Lepvrier *et al.*, 2004; Owada *et al.*, 2007) and higher-grade facies (amphibolite to granulite) within the KTM (Maluski *et al.*, 2005). Osanai *et al.* (2008) reported the age of granulite-facies metamorphism resulting from the decompression of eclogite to granulite, indicating crustal thickening and exhumation. This metamorphism occurred concurrently with the emplacement of S-type granites such as the Hai Van granite, which intruded at ~245-225 Ma (Pham *et al.*, 2015) and is interpreted to be related to post-collisional extensional tectonics.

Local geology

Host rocks: The host rock of the mineralisation in the Kon Ra area is part of the Kham Duc metamorphic sequence aged Neoproterozoic (Figure 2). This sequence is composed

of ten rock types, including: Meta-ultramafic/ pyroxenite; metagabbro; metaplagiogranite, metacarbonate, amphibolite, amphibole gneiss, anthophyllite-cordierite gneiss, biotite gneiss, crystalline schist and minor, thin (<0.5 m) layers of chert. This sequence dominates the study area and is intruded by O-S, Permian - Triassic (P-T) and Jurassic intrusions in and around the Kon Ra area. The Kham Duc formations are extensively deformed, migmatized, and exhibit complex folding with predominantly northeast-southwest to submeridional structural trends, and less commonly, northwest-southeast trends.

The metamorphic rocks of magmatic origin within the Kham Duc complex exhibit diverse petrochemical features. Metagabbro and some amphibolite show alkaline affinities, while the remaining rocks are distinctly subalkaline. Amphibole gneisses belong to the calc-alkaline series, while other rocks primarily align with the tholeiitic series, resembling the characteristics of oceanic crustal magmatic rocks (as defined by tholeiitic geochemical traits).

Magmatism: In the Kon Ra area, magmatic activities associated with both Caledonian and Indosinian events has been recorded in many historical studies (e.g., Tran *et al.*, 2014; Nguyen *et al.*, 2021; Hung *et al.*, 2022). During the earlier phases, Dien Binh I-type granodiorite and Chu Lai S-type granitogneiss were observed in the west and east of the Kon Ra area, respectively (Figure 2). In the later phases, the ~240 Ma S-type granite of the Hai Van Complex (Niem *et al.*, 2021) was widely encountered in the area and in

many drill holes, where it intrudes the mineralised zones (Figures 2, 3a). The I-type granite of the Ben Giang-Que Son Complex has been mapped north of the Kon Ra area. The rocks of this complex in both TSB and KTM have been dated to ~290-260 Ma. The youngest magmatism recorded in the Kon Ra area is a Jurassic felsite referred to as the Kon Ra Felsite (Niem *et al.*, 2021).

Based on our detailed core logging data in the Kon Ra deposit centre, a 3 m-wide granodiorite dyke was observed at the contact zone between the mineralisation and its host sequence, where the rocks were strongly altered and extremely deformed (Figure 3b). This granodiorite is composed of plagioclases, amphibole, biotite and quartz that could be either grouped into the O-S Caledonian Dien Binh granite or the P-T Indosinian Ben Giang-Que Son granite.

METHODOLOGIES AND SAMPLE SELECTION

Methodologies

Field mapping, core logging and petrography: Field mapping and detailed core logging in combination with petrography were used to investigate the Cu-Au mineralisation characteristics in the Kon Ra area. These methods provide details of ore paragenesis, textures and mineralogical assemblage for each hydrothermal episode. The alteration styles associated with the mineralisation and host rocks were carefully studied to determine their genetic relationship to mineralisation.

Sulfur isotopes: Pyrite, chalcopyrite and pyrrhotite from Cu-bearing hydrothermal veins in drill core and at surface were selected for this study. The sulphides were drilled with a dentist-size diamond drill to recover at least 0.35 mg of fine sulphide powder for each sample. The sulphide powder samples were analyzed at the Central Science Laboratory at the University of Tasmania using flash combustion isotope ratio mass spectrometry (varioPYRO cube coupled with Isoprime100 Mass Spectrometry) to determine the $^{34}\text{S}/^{32}\text{S}$ ratios. This technique involved oxidizing sulphides at high temperatures to collect the SO_2 gas produced that was collected in a trap. The SO_2 was then separated from other combustion by-products and then fed into the mass spectrometry where the $^{34}\text{S}/^{32}\text{S}$ ratios were measured against a reference gas. The stable isotope abundances were reported as delta (δ) values as deviation from standards in parts per mil (‰) using the following equation:

$$\delta^{34}\text{S} (\text{‰}) = [(R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000]$$

Where $R = ^{34}\text{S}/^{32}\text{S}$. The values $\delta^{34}\text{S} (\text{‰})$ are reported with respect to the CDT (Canon Diablo Troilite). Two international standard samples with known isotopic composition were analyzed after every four samples. The accuracy of the $\delta^{34}\text{S}$ results obtained is $\pm 0.2\text{‰}$. The detailed analytical procedure of this method has been described in Grassineau *et al.* (2001).

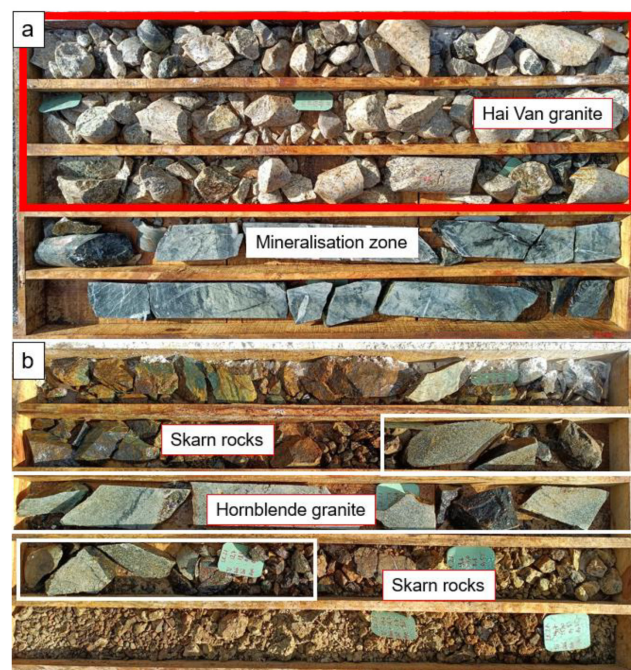


Figure 3: Drill core images showing granitic rocks intersected in drill hole LK21 and their association with Cu-Au mineralisation in the Kon Ra area: a. ~240 Ma Hai Van S-type granite intruding the mineralised zone; b. Undated hornblende granite linked to skarn metasomatism and Cu-Au hydrothermal mineralisation.

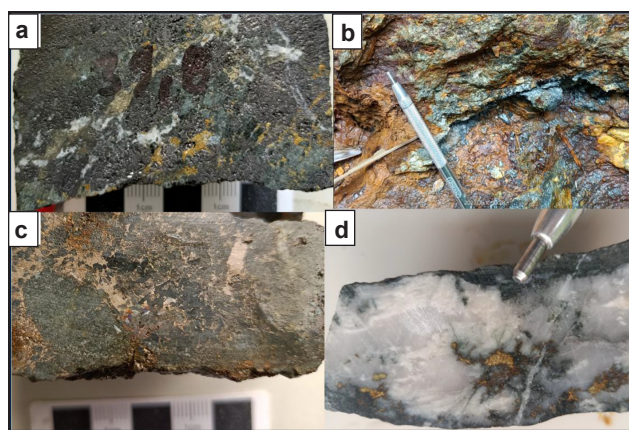


Figure 4: Representative syn-ore hand specimen images from skarn ore zones collected for sulfur isotopic analyses: a. Chalcopyrite and pyrite from drill hole LK21@39.8m; b. Chalcopyrite associated with molybdenite from an outcrop; c. Pyrrhotite from drill hole LK06@102.8m; d. Chalcopyrite from a quartz-sulphides veins at drill hole LK8@87.2m.

Sample collection

A total of 15 sulphide samples, including chalcopyrite, pyrite and pyrrhotite, were collected for sulfur isotope analyses. All samples were collected from syn-mineralisation stages within the high-grade copper ore zones and the surrounding skarn alteration halo, where sulphides are abundant and quartz is present only as a minor mineral, except for sample LK8@87.2m (Figure 4).

RESULTS

Mineralisation characteristics

The Kon Ra copper mineralisation area covers ~30 km² and is divided into three sub-zones: Kon Ra (central), Kon Nhan (south), and Kon Long (north; Figure 2). In this region, 19 hydrothermal ore bodies have been identified, hosted within the Kham Duc metamorphic complex composed of pyroxenite, amphibolite, and meta-carbonate rocks interbedded with quartz-mica schist. These bodies are typically ~2-10 m thick and 90-200 m long, with some exceptions extending to ~900 m in length. The maximum depth of mineralisation has not yet been determined. The ore exhibits a variety of textures, including pseudo-foliated veins, thin veins, stockworks, pods, clusters, and disseminations within skarn alteration zones. The mineralisation veins are typically less than 3 cm thick. The average copper content ranges from ~0.5% to ~1.9%, with a common range of 0.5–0.6%. The presence of gold within the mineralised zone is inconsistent. In several ore bodies, due to limited sampling, gold content has not yet been systematically recorded. For orebodies that are shown to contain Cu-Au mineralisation, the average gold grade is less than 1 g/t, with a typical range of 0.2-0.3 g/t.

Field surveys and petrographic analysis indicate that mineralisation at the Kon Ra ore field exhibits many

characteristics of skarn mineralisation where skarnification predominantly occurs within calcium-silicate rocks along metamorphosed carbonate-schists composed of fine-grained marble and pyroxenite. Pyroxene is interpreted to be either a product of regional metamorphism or the result of metasomatic replacement during the interaction between magmatic rocks and carbonate rocks. The skarn rock minerals observed in the ore zones from this study include pyroxene, garnet, amphibole, biotite, phlogopite, and magnetite. Niem *et al.* (2021) also observed wollastonite in altered rock from the ore zone. The ore is typically sulphide-rich and contains a small amount of quartz. The hydrothermal alteration minerals associated with Cu (±Au) stages include quartz, secondary amphiboles (actinolite, tremolite), epidote, chlorite, sericite, clay minerals, carbonate, and sulphides (primarily chalcopyrite and pyrite, pyrrhotite, with subordinate arsenopyrite, molybdenite, and marcasite. Other sulphides such as cubanite, chalcocite, malachite, sphalerite, and native gold were not observed in this study but were described in Niem *et al.* (2021).

Paragenesis:

The mineralisation in the Kon Ra ore field is characterised by distinct skarn formation stages and subsequent hydrothermal processes. The key stages and their corresponding mineral assemblages are presented in Table 1 and Figure 5. They can be divided into the following stages: contact metasomatism stage (prograde metamorphism, pre-ore); hydrothermal stages (syn-ore, retrograde metasomatism) and late hydrothermal stages (post-ore).

Pre-ore stage1: Skarn formation

This stage is primarily characterised by the formation of skarn rock composed mainly of pyroxene, amphibole, fine-grained carbonate, and to a lesser extent, biotite, phlogopite and magnetite (e.g., Figures 5 and 6; this study) and wollastonite (Niem *et al.*, 2021). Distinguishing between pyroxene and amphibole formed by contact metasomatism and those from regional metamorphism within the samples can be challenging. However, the presence of associated minerals such as biotite, garnet, magnetite, and phlogopite in alteration zones helps to differentiate them. Pyroxene, magnetite and biotite are the dominant minerals in the skarn rock. Garnet is sparsely distributed and only rarely found in small quantities within the ore zone (Figure 5b). Magnetite is locally aligned with the *S*₁ texture of the host rock (Figure 5c). The sulphides at this stage are limited to trace amounts of pyrite, which is rarely found in the samples.

In the drill cores, an approximately 3m long of I-type granitic dyke has intruded the metamorphosed Kham Duc Complex, leading to the contact metasomatism and the mineralised zone. At the contact between the dyke and the mineralisation zone, the rock was deformed and intensely weathered. Consequently, the initial evidence of metasomatism and mineralisation was partially wiped out (Figure 3b).

Table 1: Mineral paragenesis at the Kon Ra Cu-Au deposits.

Mineral	Stage 1 (pre-ore)	Stage 2 (syn-ore)	Stage 3 (post-ore)	Stage 4 (post-ore)	Stage 5 (post-ore)	Notes
Pyroxene	—					This study
Garnet	---					This study
Amphibole	—	—				This study
Biotite	—					This study
Phlogopite	—					This study
Wollastonite	---					Niem <i>et al.</i> , 2021
Magnetite	—	—				This study
Pyrite		—	---			This study
Chalcopyrite		—				This study
Pyrrhotite		---				This study
Molybdenite		---				This study
Marcasite		---				This study
Arsenopyrite		---				This study
Chalcocite		---				Niem <i>et al.</i> , 2021
Sphalerite		---				Niem <i>et al.</i> , 2021
Gold		---				Niem <i>et al.</i> , 2021
Epidote		—				This study
Chlorite		—	—			This study
Sericite		—	—			This study
Quartz		---	—			This study
Calcite	---	—	—	—		This study
Clay		—	—			This study

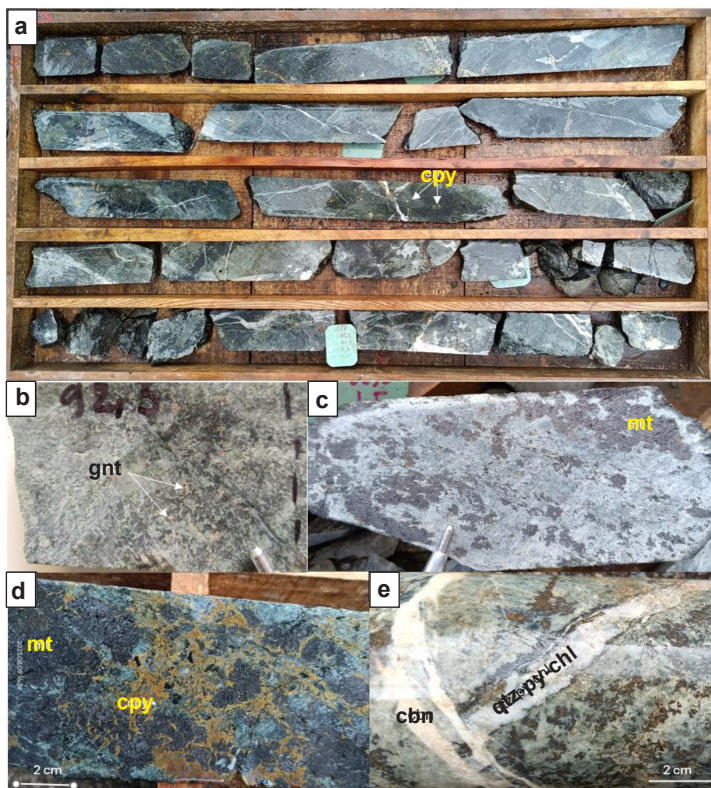


Figure 5: Representative images of mineralisation stages in the Kon Ra area: a. Five meters of chalcopyrite (Cpy)-rich ore zone in drill hole LK21; b. Skarn rock with pyroxene (dark green), garnet (gnt) and amphibole (green). Sample from drill hole LK21@92.5 m; c. Magnetite (mt) from Stage 1 exhibiting fabric aligned with the S_1 texture of the host rocks. Sample from drill hole LK21@39.8m; d. Chalcopyrite (Cpy) from Stage 2 associated with secondary amphibole (green), cross-cutting and replacing earlier magnetite (mt). Sample from drill hole LK21@85.5 m; e. Stage 2 mineralisation cross-cut by Stage 3 quartz-pyrite-chlorite (qtz-py-chl) veins and Stage 4 carbonate (cbn) veins.

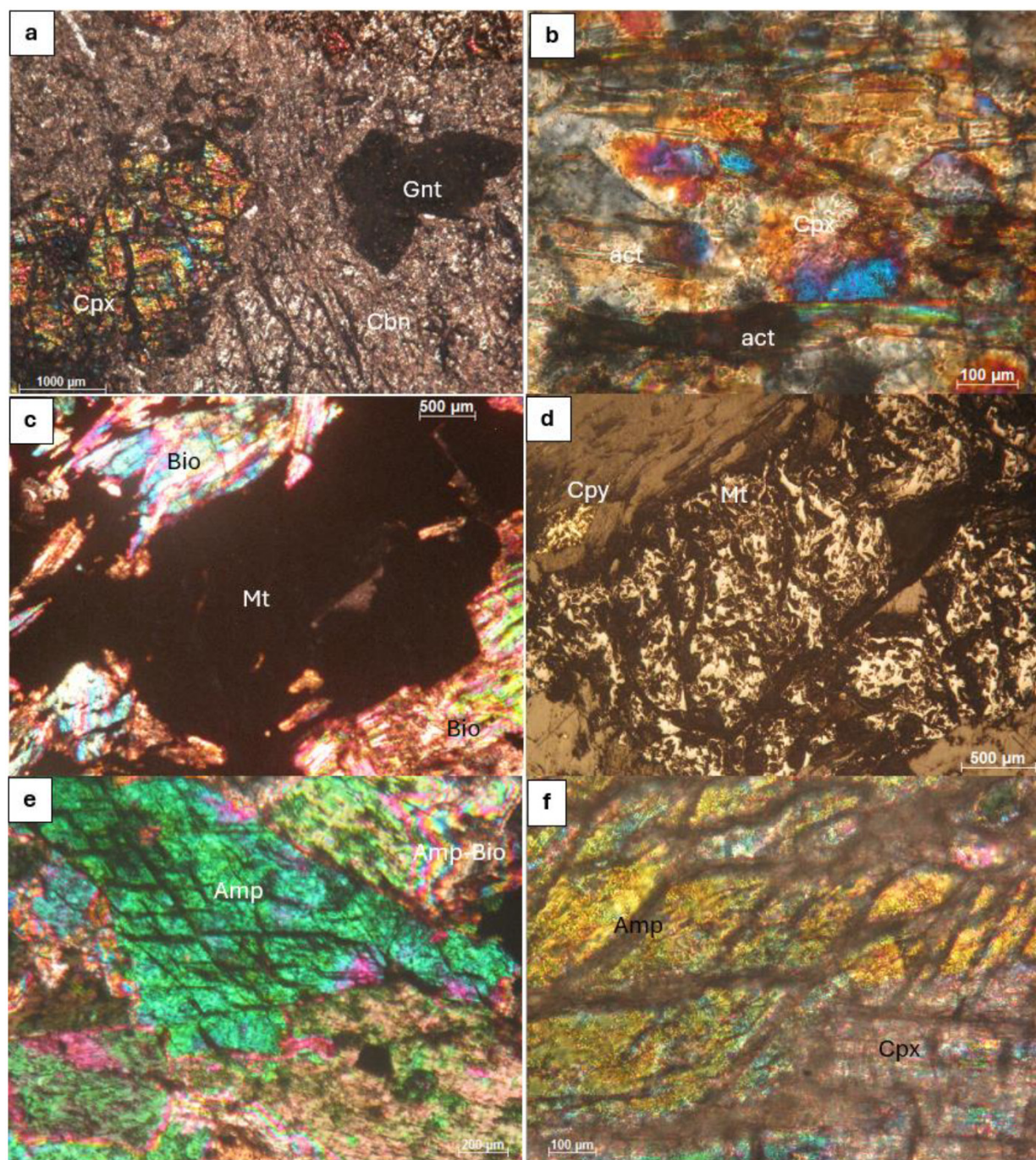


Figure 6: Representative microphotographs of minerals formed during Stage 1 (prograde metasomatism) in the Kon Ra area: a. Mineral assemblage of pyroxene (cpx), garnet (gnt), and carbonate (cbn) in skarn rock from drill hole LK21@92.5m; b. Actinolite (act) from Stage 2 replacing Stage 1 pyroxene (cpx). Sample from drill hole LK21@26.9m; c-d. Biotite (bio) coexisting with magnetite (mt) under transmitted light (c) and reflected light (d) in skarn rock. Sample from drill hole LK21@26.9 m; e. Amphibole (amp) in skarn rock, partially altered to biotite (bio). Sample from drill hole LK8@50 m. f Close-up view of amphibole (amp) and pyroxene (cpx) from e.

Syn-ore stage 2 (retrograde metamorphism)

This stage typically marks the onset of hydrothermal activity and presents the main Cu mineralisation episodes just after the prograde metamorphism. The skarn rocks altered by hydrothermal fluids are extensively distributed within the calc-silicate host-rocks of the Kham Duc sequence,

developing along pyroxenite layers that were metamorphosed from dolomite. Stage 2 highlights the formation of a complex mineral assemblage, dominated by Cu-sulphide mineralisation, associated with characteristic retrograde metamorphism in a skarn environment. The sulphides in this stage mainly include chalcopyrite, pyrite and pyrrhotite

with subordinate molybdenite and marcasite (Figures 7a, b). The pyrrhotite occurs locally as massive veins or patches in certain areas within the orebody while molybdenite typically occurs in low concentrations alongside high concentrations of pyrrhotite in certain pockets. Molybdenite locally displays clear coexistence with chalcopyrite (Figure 7c). This stage can be divided into two sub-stages: (1) Stage 2a with the

formation of secondary amphiboles such as actinolite (observed under a microscope) and possibly tremolite (visible to the naked eye and under a hand lens, and documented in previous studies, e.g., Niem *et al.*, 2021) and (2) Stage 2b with the formation of hydrothermal alteration minerals and sulphide minerals. The veins of this late sub-stage usually exhibit stockwork and locally en-echelon vein structures.

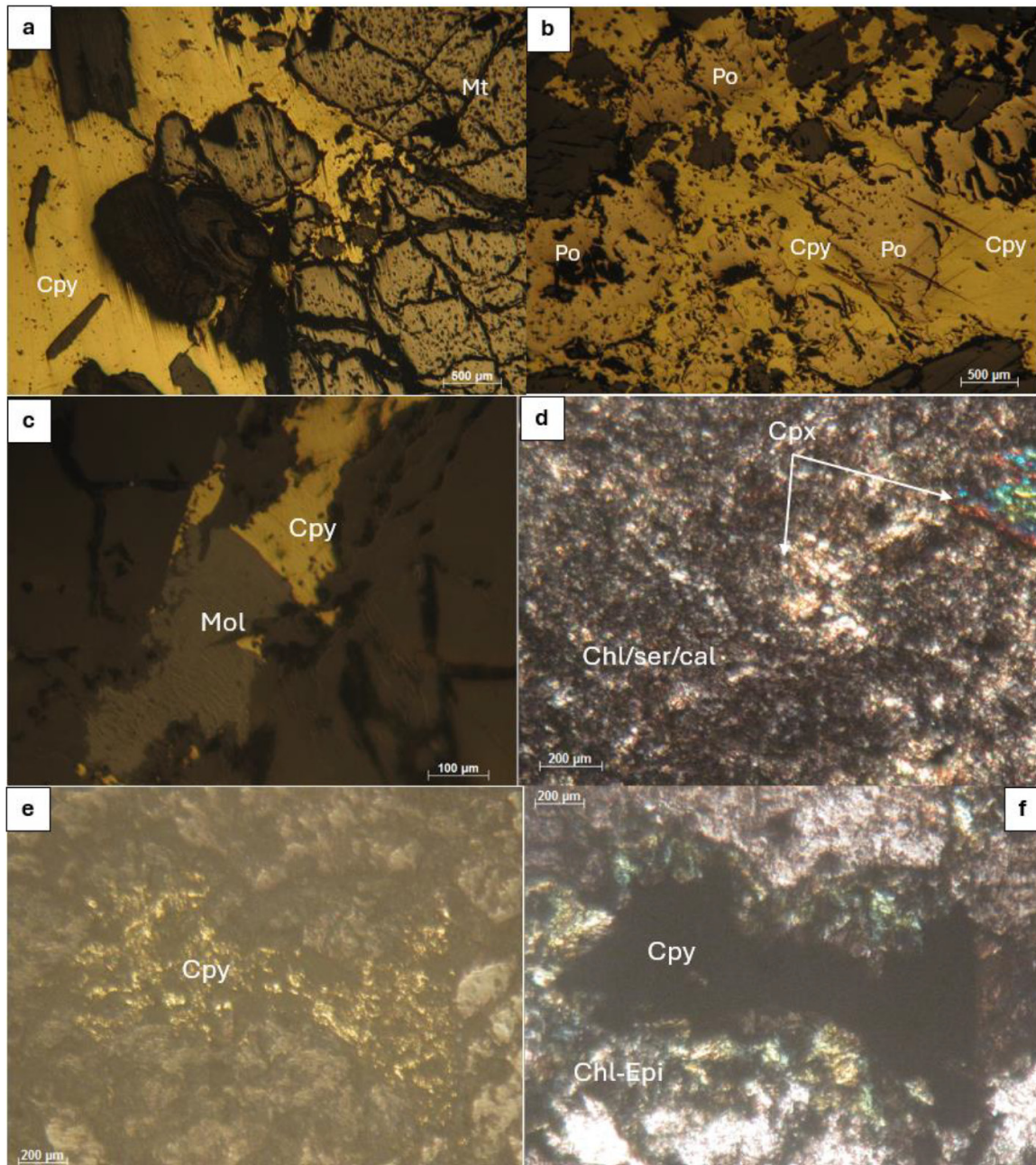


Figure 7: Representative microphotographs of Stage 2 mineralisation showing sulphide, alteration minerals, and their microtextures: a. Stage 2 chalcopyrite (Cpy) crosscutting Stage 1 magnetite (Mt) in drill hole LK21@39.8m; b. Assemblage of coexisting chalcopyrite (Cpy) and pyrrhotite (Po) from drill hole LK21@39.8m; c. Coexisting molybdenite (Mol) and Cpy characterised by a planar contact relationship, from outcrop sample KR01; d. Hydrothermal alteration assemblage of chlorite, sericite, and calcite (Chl-ser-cal) replacing pre-existing minerals, with remnant pyroxene (Cpx) in drill hole LK6@104.4m; e-f. Disseminated chalcopyrite (Cpy) surrounded by a chlorite-epidote (chl-epi) alteration halo in drill hole LK8@87.2m under reflected light (e) and transmitted light (f).

The altered minerals predominantly include quartz, chlorite, and epidote with subordinate sericite (Figures 7d, f). These alteration minerals often exhibit concentric structures around sulphide veins, pods or pockets, reflecting the crystallization sequence of alteration minerals that form first and enclose later sulphide minerals in the centre (Figures 7e, f).

Post-ore stages

These include three phases of hydrothermal veins characterised by quartz, carbonate, quartz-carbonate (+/- pyrite) veins that cross-cut mineralisation zones as below:

- Stage 3: This stage is characterised by quartz-chlorite-pyrite veins and stockworks at specific locations within the ore zone, which crosscuts Cu-bearing ore veins (e.g., Figure 5e). This hydrothermal stage is locally distributed, uncommon, and often associated with the two-mica granite of the Hai Van Complex, which intersects the ore zone. The alteration minerals in this vein stage include chlorite, sericite, calcite and clay minerals.
- Stage 4: This stage is marked by sharp, well-defined quartz veins, quartz-carbonate veins (+/- pyrite), and carbonate veins that crosscut earlier hydrothermal stages (Figure 5e). Stage 4 hydrothermal veins are widespread across the Kon Ra area.
- Stage 5: Late carbonate veins crosscutting earlier carbonate veins, as observed in petrographic thin sections.

Sulfur isotopes

The isotopic composition of sulfur for sulphides collected from the syn-ore stages within the ore zones of

the Kon Ra area is presented in Table 2. The $\delta^{34}\text{S}$ values obtained from 15 samples of chalcopyrite, pyrite and pyrrhotite range from -7.3‰ to 0.31‰. Specifically, nine samples have $\delta^{34}\text{S}$ values ranging from -4.87‰ to 0.32‰ while six samples have lighter sulfur with $\delta^{34}\text{S}$ values ranging from -7.3‰ to -5.1‰.

DISCUSSION

Sources of Cu-Au ore

The $\delta^{34}\text{S}$ values from the syn-ore stages at the Kon Ra Cu-Au deposits range from -7.3‰ to 0.31‰ (n=15) with most values falling between -4.87‰ and 0.32‰ (n=9). The potential isotopic reservoirs for sulfur, as described in Rollinson (1996), include: (a) igneous sulfur sources with similar isotopic signatures to meteorites, having $\delta^{34}\text{S}$ values close to 0‰; (b) seawater sulphates with variably heavy $\delta^{34}\text{S}$ isotopic values ranging from +10 to +35‰ during the Cambrian to present; and (c) modern seawater sulphates with $\delta^{34}\text{S}$ values from +18 to 20‰. Sedimentary environments can contain highly variable $\delta^{34}\text{S}$ values ranging from -70 to >+20‰ (Ohmoto & Rye, 1979). Sulphides in magmatic hydrothermal systems commonly have $\delta^{34}\text{S}$ values centred around 0.00‰, though they can reach up to 10‰ depending on conditions involving the temperature and pH of the mineralising fluids and the original isotopic composition (Ohmoto & Rye, 1979). The range of $\delta^{34}\text{S}$ values produced within a single deposit is also influenced by isotopic fractionation processes between the sulfur source and produced sulphides (Ohmoto & Rye, 1979).

The $\delta^{34}\text{S}$ range in Kon Ra is largely consistent with those of magmatic-origin systems (Figure 8) and corresponds to the

Table 2: Sulphur isotopic data at the Kon Ra Cu-Au deposit.

Order	Name	Minerals	Weight (mg)	S34	Corrected $\delta^{34}\text{SCDT}$
1	LK21-26.9	Chalcopyrite	0.60	-1.71	-7.04
2	LK21-30	Chalcopyrite	0.55	-1.72	-7.05
3	LK21-39.8	Chalcopyrite	0.66	0.12	-5.10
4	LK21-48.8	Pyrite	0.40	0.33	-4.87
5	LK21-63	Chalcopyrite	0.68	1.68	-3.45
6	LK21-68.5	Chalcopyrite	0.62	1.49	-3.65
7	LK21-74.3	Pyrite	0.37	2.46	-2.62
8	LK21-77_3	Chalcopyrite	0.58	-0.02	-5.24
9	LK06-90	Pyrite	0.40	-1.32	-6.62
10	LK06-102.8	Pyrrhotite	0.56	-1.96	-7.30
11	LK08-71.1	Pyrite	0.36	3.69	-1.32
12	CR02	Chalcopyrite	0.57	1.23	-3.92
13	LK08-83.1	Pyrite	0.45	5.11	0.19
14	LK08-87.2	Chalcopyrite	0.61	1.39	-3.76
15	LK08-97.2	Pyrite	0.46	5.24	0.32

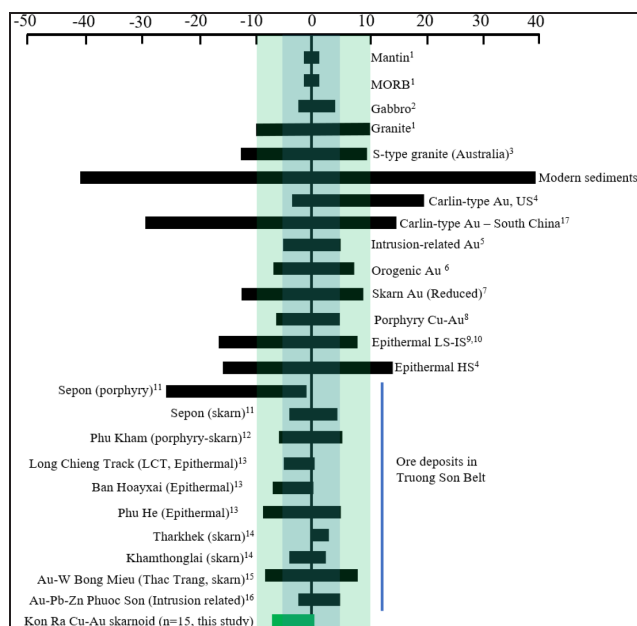


Figure 8: The $\delta^{34}\text{S}$ values from the Kon Ra Cu-Au deposits in comparison with those from different sulfur reservoirs and deposit types in the nearby Truong Son Belt and South China Block: 1. Rollinson (1993); 2. Sasaki & Ishihara (1979); 3. Coleman (1977); 4. Cline *et al.* (2005); 5. Thompson & Newberry (2000); 6. Hodkiewicz *et al.* (2009); 7. Khin Zaw *et al.* (2007); 8. Cooke & Simmons (2000); 9. Christie *et al.* (2007); 10. Camprubi & Albinson (2007); 11. Cromie (2010); 12. Backhouse (2004); 13. Manaka (2008); 14. Hotson (2009); 15. Lee (2010); 16. Manaka (2014).

$\delta^{34}\text{S}$ values observed in numerous magmatic-related Au and Cu-Au deposits, such as intrusion-related hydrothermal gold deposits, skarn gold deposits, porphyry deposits, and shallow hydrothermal systems (high-sulfidation [HS], low-sulfidation [LS], and intermediate-sulfidation [IS]). Given the context of tectonic setting, magmatism, and skarn mineralisation characteristics in the Kon Ra area, the $\delta^{34}\text{S}$ values (from -7.3‰ to 0.32‰; $n=15$) in the deposits are predominantly derived from a magmatic source of a skarn mineralisation system, with minor input of lighter sulfur derived from slightly reduced sedimentary layers influenced by organic bacterial activity. The sulfur isotope composition of the Kon Ra Cu-Au deposit, when compared to those from several endogenous deposits within the Truong Son Belt, exhibits strong similarities to the skarn Au-W deposits in Bong Mieu, the shallow hydrothermal gold deposits associated with porphyry systems in Phu Kham (Laos), and Cu-Au porphyry-skarn deposits in Sepon deposits (Laos; Figure 8). These deposits predominantly feature ores of magmatic origin, with minor contribution from host rocks.

Mineralisation styles and deep mineralisation potential

The Kon Ra deposits present mineralisation features consistent with skarn Cu-Au systems. The presence of pyroxene, garnet, amphibole, and magnetite in the skarn

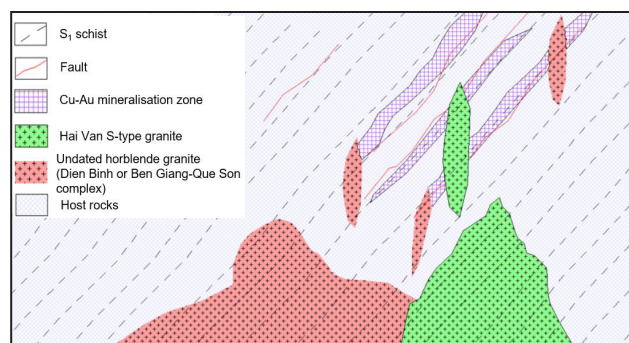


Figure 9: Interpreted schematic model of skarn Cu-Au mineralisation in the Kon Ra area. A conceptual cross-section illustrating the spatial relationships among the buried intrusion, host rocks, skarn alteration zones, and known Cu-Au mineralisation. The model highlights the interpreted downward potential for deeper mineralisation associated with skarn zones proximal to the intrusive contact.

assemblage, together with hydrothermal alteration minerals such as chlorite, epidote, and quartz, indicates a signature of skarn metasomatism ranging from prograde metasomatism to retrograde hydrothermal events. Notably, skarnification occurred primarily within calcium-silicate rocks, highlighting the importance of lithological controls on mineralisation. The paragenetic sequence of the mineralisation is divided into a pre-ore, a syn-ore, and a post-ore stages. The pre-ore stage is dominated by contact metasomatic processes that formed primary skarn minerals, with pyroxene and amphibole as the principal phases. The syn-ore stage corresponds to retrograde metamorphism, during which hydrothermal fluid activity facilitated the deposition of Cu-bearing sulphides such as chalcopyrite, pyrite, and pyrrhotite.

Global studies of well-documented skarn Cu-Au systems have shown that the pyroxene/garnet ratios are useful indicators for assessing the proximity to mineralisation zones. Specifically, moving outward from endoskarn (adjacent to intrusions) toward exoskarn (within host rocks), the garnet/pyroxene ratio typically decreases: garnet volumes diminish, and pyroxene becomes more dominant (e.g., Atkinson & Einaudi, 1978; Meinert, 1997; Meinert *et al.*, 2005). At Kon Ra area, pyroxene is abundant, whereas garnet is rare, suggesting that current mineralisation is distal from the intrusion-host rock contact zone. This garnet-poor signature indicates the potential for more significant Cu mineralisation at depth, where higher garnet/pyroxene ratios may occur. Such zones may be spatially associated with deeper granite stocks linked to a larger intrusive body located at greater depths (Figure 9).

Interpretation for timing of mineralisation

The Cu-Au mineralisation at Kon Ra is associated with minor content of molybdenite. Thus, the most effective method for determining the timing of mineralisation would be Re-Os geochronological analysis of molybdenite. However, since this method has not been applied, the timing of mineralisation can be inferred based on the regional

geological history and the mineralisation characteristics of the Kon Ra area as discussed below.

The Kon Ra Cu-Au mineralisation occurs within the context of two significant tectono-magmatic-mineralisation episodes in the Truong Son Belt (TSB) and the Kon Tum Massif (KTM): the O-S and P-T events. The earlier episode is attributed to bilateral subduction and collision between the TSB and KTM along the Gondwana continental margin (Dung *et al.*, 2024). Magmatism during this period is represented by suites such as the Tra Bong, Dien Binh, and Chu Lai complexes in both the TSB and KTM (e.g., Gardner *et al.*, 2017; Nguyen *et al.*, 2021; Ngo *et al.*, 2022; Dung *et al.*, 2024; Nguyen *et al.*, 2024). Mineralisation associated with this episode has been relatively underexplored, with only limited occurrences reported, such as the Benden Cu deposits in southern Laos (Gardner *et al.*, 2017) and Zn-Pb-Cu deposits in central Vietnam (Khin Zaw *et al.*, 2014). The second major tectono-magmatic event is the Indosinian orogeny during the P-T, with regional magmatism dominated by the extensive Ben Giang–Que Son and Hai Van complexes (e.g., Dung *et al.*, 2024).

In the Kon Ra area, based on detailed core logging, Cu-Au mineralisation is genetically related to an undated hornblende granite in drill hole LK21. This magma could have originated from either the O-S Dien Binh Complex or the P-T Ben Giang - Que Son Complex. The O-S Dien Binh I-type granite occurs just west of the central mineralised zone, while the P-T Ben Giang - Que Son granite is recorded slightly farther north of the deposit. The ore textures in the Kon Ra provide limited insights into the timing of mineralisation. Fabric magnetite observed in Stage 1 and local pseudo-foliated veins are interpreted to have formed under high-temperature, high-pressure conditions or through local remobilisation and reorganisation during post-ore metamorphism. This suggests that the Kon Ra mineralisation could be related to either the O-S Dien Binh or the P-T Ben Giang-Que Son complexes, and may have formed prior to the collision between the TSB and the South China Block during the Isan orogeny.

Additionally, the en-echelon vein structures observed in Stage 2 suggest brittle deformation under temperatures below ~500°C. The post-ore stages are characterised by multiple generations of hydrothermal veins, including quartz, carbonate, and quartz-carbonate veins. These features reflect multiphase hydrothermal activity following the main ore-forming event, consistent with the broader geological evolution of the region.

CONCLUSION

The Kon Ra Cu-Au deposit is a unique example of skarn mineralisation hosted in the metamorphic Kham Duc complex, which is characterised by multi-stage mineralisation episodes. The hornblende granite associated with the Cu-Au mineralisation in this area belongs to either the Dien Binh or Ben Giang-Que Son complexes.

Mineralisation primarily occurs as hydrothermal veins, stockworks, and disseminations within the skarn rock, and it exhibits distinct prograde (pre-ore) and retrograde (syn-ore) metasomatism and alteration. The skarn rock is dominated by pyroxene with minor amount of garnet, indicating a distal skarn system and suggesting possible mineralisation at depth. The syn-ore retrograde stage is characterised by chalcopyrite, pyrite, and pyrrhotite, along with subordinate molybdenite and associated hydrothermal alteration minerals such as actinolite, quartz, epidote, chlorite, sericite, calcite and clay. The $\delta^{34}\text{S}$ values that vary from -7.3‰ to 0.31‰ (n=15) indicate a magmatic sulfur source, possibly with minor contamination of sulfur from the host rock, and are consistent with those of typical skarn systems. These study results provide better understanding of Cu-Au skarn systems in the region and their exploration. While the sulfur isotopes support the interpretation of magmatic contributions to ore formation, the identification of mineralisation stages and alteration patterns enhances exploration models for similar deposits.

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AUTHORS CONTRIBUTION

TXL is the main author who prepared the manuscript and figures. TXN, KQL, DMT provided support on the regional and deposit mapping, core logging, sampling and petrography. CM provided support for sulfur isotopic analyses. All authors reviewed the results, interpretation and edited the manuscript.

CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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