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PARAGENESA MINERAL ENDAPAN SKARN TEMBAGA PROSPEK TAMBULUN, SULIT AIR, SUMATERA BARAT

MINERAL PARAGENESS OF COPPER SKARN DEPOSITS IN TAMBULUN PROSPECT, SULIT AIR, WEST SUMATERA

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Abstrak

Prospek Tambulun, Sulit Air, Kabupaten Solok, Sumatera Barat, merupakan salah satu lokasi yang mengindikasikan adanya sistem mineralisasi skarn tembaga (Cu). Penelitian ini bertujuan untuk mengidentifikasi paragenesa mineral pada sistem skarn tersebut melalui analisis petrografi dan mikroskopi bijih. Proses pembentukan skarn disebabkan oleh intrusi granodiorit Sulit Air yang menerobos batugamping Formasi Tuhur menghasilkan zona alterasi berupa eksoskarn (alterasi garnet–piroksen, garnet–piroksen–wollastonit, piroksen–kuarsa ± epidot ± klorit) dan endoskarn (alterasi piroksen–k-feldspar–klorit–epidot). Pembentukan skarn dibagi menjadi empat tahap utama, yaitu: (1) metamorfisme isokimia, (2) tahap prograde dengan pembentukan mineral kalk-silikat bersuhu tinggi, (3) tahap retrograde dengan munculnya mineral bersuhu lebih rendah seperti epidot dan kalsit, dan (4) tahap supergen. Mineralisasi tembaga dominan berupa kalkopirit, bornit, kovelit, dan kalkosit. Pada tahap prograde, kalkopirit mengisi rekahan bersama urat kuarsa dalam zona garnet–piroksen. Tahap retrograde dicirikan oleh kehadiran bornit dan kalkosit bersama urat kalsit dan epidot yang memotong zona alterasi garnet–piroksen–wollastonit. Fase supergen menunjukkan mineralisasi sekunder seperti kovelit, hematit, malakit, azurit, dan krisokola yang mengisi rekahan dan pori batuan.

Kata kunci: paragenesa mineral, prospek Tambulun, skarn Cu, Sulit Air

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Abstract

The Tambulun prospect in Sulit Air, Solok Regency, West Sumatra, shows strong indications of a copper (Cu) skarn mineralization system. This study aims to identify the mineral paragenesis through petrographic and ore microscopy analyses. Skarn formation resulted from the intrusion of Sulit Air granodiorite into limestone of the Tuhur Formation, triggering interaction between magmatic fluids and carbonate rocks. This produced alteration zones consisting of exoskarn (garnet–pyroxene, garnet–pyroxene–wollastonite, pyroxene–quartz ±epidote ±chlorite) and endoskarn (pyroxene–k-feldspar–chlorite–epidote). Skarn evolution is divided into four stages: (1) isochemical metamorphism, (2) prograde stage with high-temperature calc-silicate minerals, (3) retrograde stage with epidote, actinolite, and calcite, and (4) supergene stage from meteoric water leaching. Copper mineralization is dominated by chalcopyrite, bornite, covellite, and chalcocite. Chalcopyrite fills fractures with quartz in the prograde zone, while bornite and chalcocite occur with calcite and epidote veins in the retrograde stage. Supergene minerals such as covellite, malachite, azurite, hematite, and chrysocolla fill fractures and pore spaces.

Keywords: *mineral paragenesis, Tambulun Prospect, Cu skarn, Sulit Air*

I. INTRODUCTION

Indonesia is located in the Pacific Ring of Fire zone which is characterized by the presence of active volcanic arcs. Magmatic activity that took place from Pre-Tertiary to Tertiary. Fifteen Late Mesozoic and Cenozoic magmatic arcs have been identified in Indonesia and more than 98% of copper gold mineralization is produced from middle Tertiary or younger magmatic arcs [1]. In addition, limestone is widespread in Indonesia, its distribution in the western part of Sumatra, West Java, Central Java, East Java and Madura. The presence of limestone in Sumatra is Triassic, Jurassic, Cretaceous, and Paleogene [2].

Skarn is a calc-silicate rock formed by the replacement process of carbonate rocks during regional metamorphism or contact metasomatism processes associated with igneous intrusions (Pirajno, 2009). Some significant examples of metal skarn deposits in Indonesia are the Cu-Au skarn at Mount Bijih, Ertsberg [3], [4], [5]. Batu Hijau [6], and the Fe-Pb-Zn-Ag skarn at Ruwai, Central Kalimantan [7], [8], [9], [10]. In Sumatra, the potential for skarn deposits is also quite developed, especially those associated with granitoid intrusions of Middle Jurassic to Early Cretaceous age, such as in Muarasipongi [11], Singkarak, and Sulit Air [12].

The Sulit Air area indicates the presence of copper (Cu) mineralization associated with a skarn deposit system, but in-depth scientific studies of the mineralization system in this area are still relatively limited. Several previous studies have examined certain aspects, such as changes in rare earth element mass transfer during the Cu skarn mineralization process [13], geochemical characteristics and tectonic environment of Cu skarn formation [14], as well as geology and hydrothermal alteration patterns [15]. In addition, studies on the control of geological structures on the distribution of alteration and Cu skarn mineralization in this area have also been conducted [16]. However, to date there has been no research that specifically discusses the aspects of mineralogy, mineral paragenesis, and their relationship to the Cu skarn formation process in the Sulit Air area. Mineral paragenesis research in the skarn system is important to determine the sequence of mineral formation and the relationship between minerals and mineralization. This research helps in supporting mineral exploration activities, especially for Cu skarn deposits in the Sumatra region, especially Sulit Air and its surroundings.

II. LITERATURE REVIEW

Skarn deposits are a type of hydrothermal deposit formed through the interaction of magmatic fluids with carbonate rocks. This interaction produces mineral zones that develop gradually from high temperature conditions (prograde stage) to lower temperatures (retrograde stage) [17]. Genetically, skarn formation involves isochemical contact metamorphism and metasomatism processes that cause heat and solution transfer from the intrusion to the adjacent rocks [18]. Skarn formation occurs in three stages: isochemical metamorphism, metasomatism, and retrograde alteration [19]. Skarns are generally zoned and can be classified into endoskarns and exoskarns based on their position relative to the intrusion [17], [18].

Based on the Solok Sheet Geological Map [20], the Sulit Air area is composed of the Tuhur Formation Limestone Member, intrusive rocks, the Brani Formation, the Lower Member of the Ombilin Formation, and undissociated volcanic materials (Figure 1). Copper and gold (Cu-Au) mineralization in the Sulit Air area is closely associated with the crystalline limestone of the Triassic Tuhur Formation. This limestone underwent contact metamorphism into marble due to the intrusion of granodiorite and granite, which subsequently underwent alteration. The skarn alteration zone consists of garnet-pyroxene alteration, garnet-pyroxene-wollastonite alteration, and pyroxene-quartz ± epidote ± chorite alteration, as well as k-feldspar-pyroxene-chlorite-epidote alteration. The distribution of alteration zones and Cu skarn mineralization in this area is strongly influenced by the presence of left-strike fault structures trending north–south (N–S) and northwest–southeast (NW–SE). These fault lines act as fluid conduits that allow the movement of metal-bearing hydrothermal solutions into the reactive zone (Figure 2) [16].

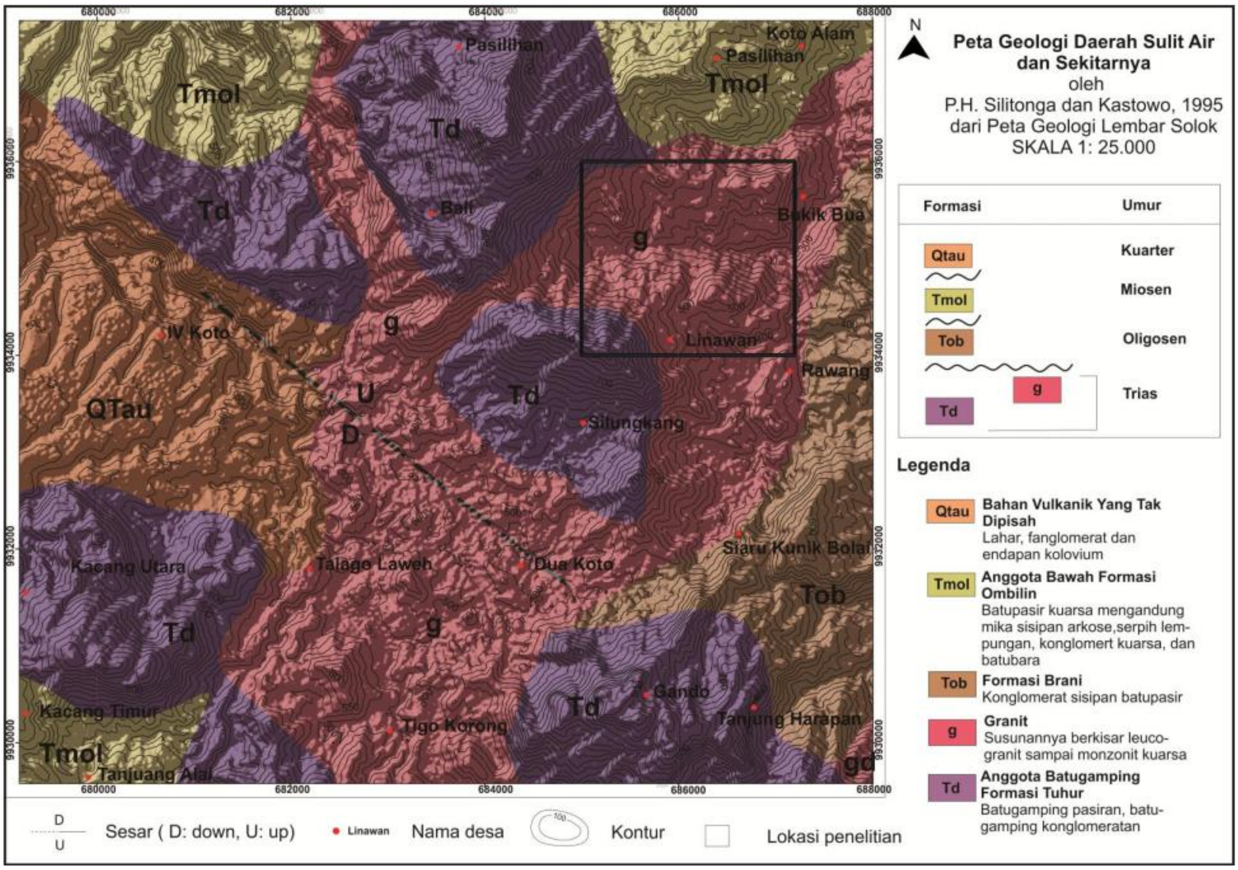


Figure 1. Geological map of the Sulit Air area, based on the geological map of the Solok sheet [20].

III. METHODS

This research was conducted by collecting geological data through geological mapping and alteration mapping activities. A total of six selected samples representing the distribution of alteration and mineralization zones were taken and further analyzed through petrographic analysis and ore microscopy. Microscopic observations used a transmitted-light microscope, using a Euromex trinocular microscope (Holland). Petrographic analysis was conducted to identify the main minerals, rock textures, and relationships between minerals. The purpose of this analysis was to identify the non-metallic minerals formed. Meanwhile, microscopic analysis of the ore was conducted on polished sections to observe metallic minerals. This analysis aims to determine the formation sequence (paragenesis) of ore minerals and their associations. The results of both analyses were then integrated to compile a mineral paragenesis in the copper (Cu) skarn deposit system at the study site.

IV. RESULTS AND DISCUSSION

A. *Mineralogical Characteristics*

Based on the secondary mineral assemblage, alteration in the study area is divided into four alteration zones: garnet-pyroxene alteration, garnet-pyroxene-wollastonite alteration, and pyroxene-quartz ± epidote ± chorite alteration, which are part of exoskarn, and k-feldspar-pyroxene-chlorite-epidote alteration, which is part of endoskarn [16] (Figure 2). Each zone has distinct mineralogical characteristics.

Pyroxene-k-feldspar-chlorite-epidote alteration

Characterized by pyroxene and k-feldspar minerals with small amounts of chlorite and epidote. This alteration is present in intrusive rocks, such as granodiorite, which intrudes carbonate rocks (Figure 3E). This alteration zone is part of endoskarn because calc-silicate minerals such as pyroxene and epidote are present in the intrusive rocks. Endoskarn forms in areas where fluid flow is more dominant (rather deep) within the intrusive body. Megascopically, rocks with this alteration are pink to greenish gray (Figure 3F). In granodiorite lithology, this alteration is dominated by pyroxene ranging from 15-40%, k-feldspar 5-15% and small amounts of chlorite, epidote, quartz with ore minerals in the form of pyrite and chalcopyrite (Figure 3G). Secondary minerals such as pyroxene, chlorite, epidote and opaque minerals are formed due to the reaction between the intrusive rock and carbonate rock, thus replacing the primary minerals in the form of hornblende and plagioclase. This alteration zone is cut by fine quartz veins measuring <2 mm, carrying metals and depositing sulfide minerals along fractures due to the structure and fractures caused by the intrusion itself (Figure 3F). Mineralization in the form of chalcopyrite with a percentage of 3%, measuring 1-3 mm which formed together with the quartz veins that cut this alteration.

Garnet-Pyroxene Alteration

Garnet-pyroxene alteration is located around the contact of the Sulit Air granodiorite intrusion with the Tuhur Marble Unit (Figure 3F). The garnet-pyroxene alteration zone forms at high temperatures after metamorphic processes transform carbonate sedimentary rocks into marble or hornfels. This alteration results from metasomatism, which causes extensive chemical changes in the composition of rocks or rock fragments, involving the transfer of chemical components as a result of interactions between the rock and fluids (solutions) in the solid phase. Garnet-pyroxene alteration is characterized by the presence of abundant garnet minerals and small amounts of pyroxene. This zone is dominated by reddish-brown garnet, varying in size from 5 mm to 35 mm (Figure 3G). Overall, the garnet-clinopyroxene zone consists of 75% garnet, 5-10% clinopyroxene, and small amounts of quartz, calcite, ore minerals such as chalcopyrite, oxide minerals, and malachite. Garnet forms first, followed by fine-grained clinopyroxene crystals measuring 0.5 to 1 mm in size within the garnet mineral. Clinopyroxene is dark green in color, prismatic, and subhedral in shape. Quartz veins cut through the pyroxene garnet zone, with a thickness of <2 mm (Figure 3G). Some quartz veins are accompanied by sulfide minerals such as chalcopyrite (Figure 7). Metals are transported by hydrothermal fluids through weak zones such as structures, lithologic contacts, or bedding planes.

Garnet-Wollastonite-Pyroxene Alteration

This alteration occurs around fault zones and near the marble face, which is relatively distant from the intrusion body (Figures 3A, 3B, 3C). This alteration zone is well exposed in the Tambulun open-pit mine and at Tambulun Waterfall. The mineral assemblage in this alteration zone is dominated by garnet (15-40%), wollastonite (15-40%), clinopyroxene (10-15%), and small amounts of sulfide minerals, such as calcite, malachite, azurite, and chrysocola. Sulfide minerals, such as bornite, chalcopyrite, covellite, and chalcocite, are abundant in this zone, compared to other alteration zones, where they are present at 15-20%. Macroscopically, greenish-yellow to light green garnet dominates this zone, varying in size from 1-2 mm (Figure 3I). Microscopically, in parallel polarization, the rock is pale (colorless) and in the appearance of crossed polarization, the color is grayish black interference, the structure is non-foliated-granofels, has a crystalloblastic-granoblastic texture, crystal size <0.1-3 mm, the mineral composition is garnet, clinopyroxene, wollastonite, calcite, opaque minerals and quartz veins (Figure 10). Garnet minerals are formed earlier and then replaced by wollastonite and clinopyroxene. Calcite, quartz, malachite and azurite in this alteration are present in the form of veins. Quartz and calcite veins have a thickness of <3 mm, and only a few of these veins are filled with ore minerals (Figures 11, 12). While malachite and azurite veins have a thickness of 10-40 mm, these veins are rich in ore minerals such as bornite, chalcopyrite and covellite (Figure 13). Mineralization in this alteration is concentrated in weak zones between bedding planes in the hostrock and fractures in open fractures caused by the structure. The presence of malachite, azurite, chrysocola, and covellite constitutes a supergene enrichment zone of primary sulfide minerals, namely bornite, chalcopyrite, and chalcocite.

Pyroxene-Quartz ± Epidote Alteration

Pyroxene-quartz alteration is present primarily around fault zones, but not entirely. The mineral assemblage in this alteration zone is dominated by clinopyroxene (25-40%), quartz (20-30%), and epidote (20-30%), with minor opaque minerals. Macroscopically, this alteration is greenish-gray, very hard, with a very fine grain size of 0.0625-1 mm, massive in structure, and still exhibits the grain texture of the parent rock and is intersected by calcite veins (Figure 3H). The calcite veins are <1 mm thick and do not contain ore minerals (Figure 8). Mineralization in the form of disseminated chalcopyrite and pyrite is present in this alteration zone and is not abundant, only around 2% (Figure 9).

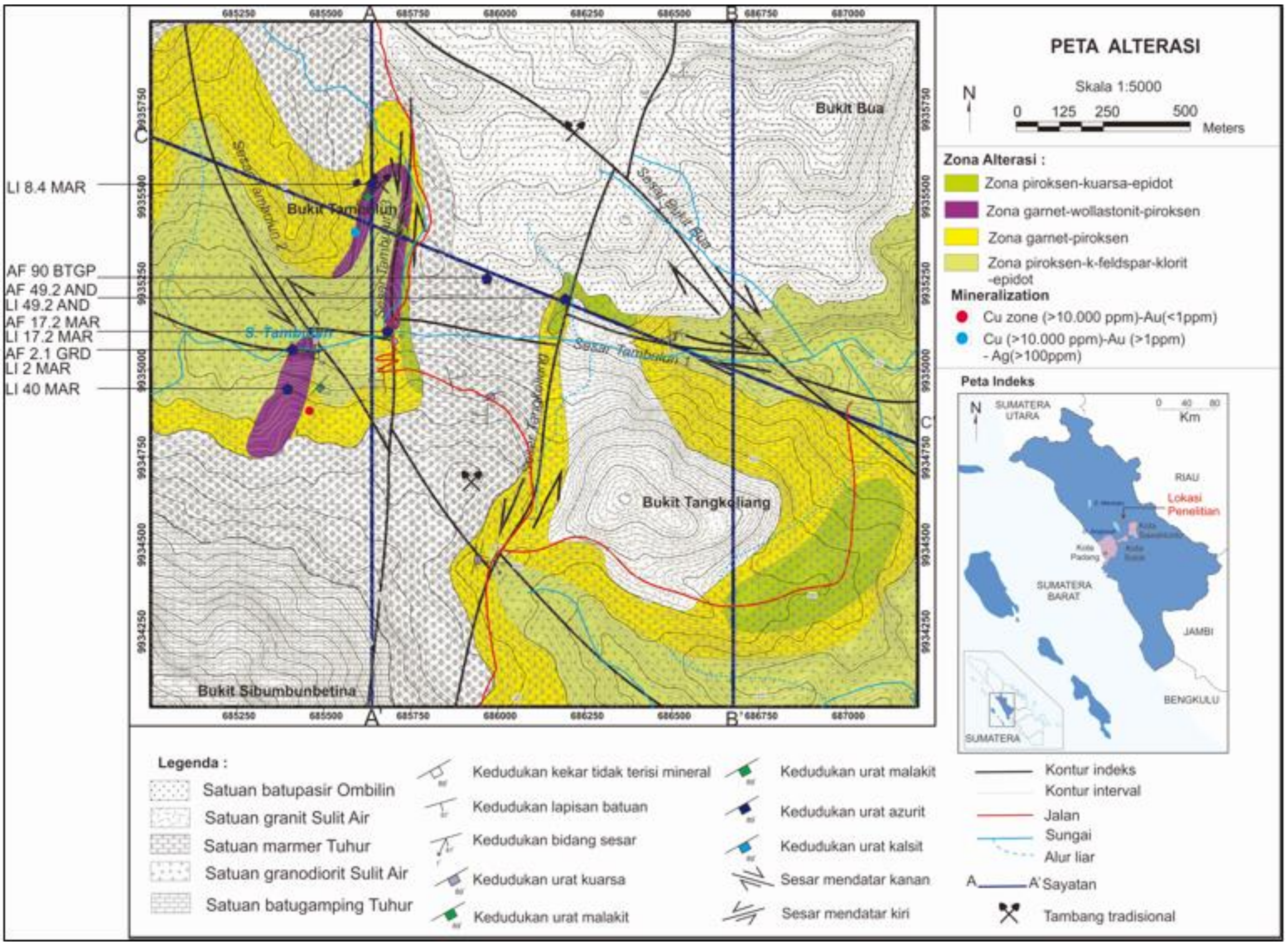


Figure 2. Sampling locations and alteration maps of the Water-Scarce area [14]

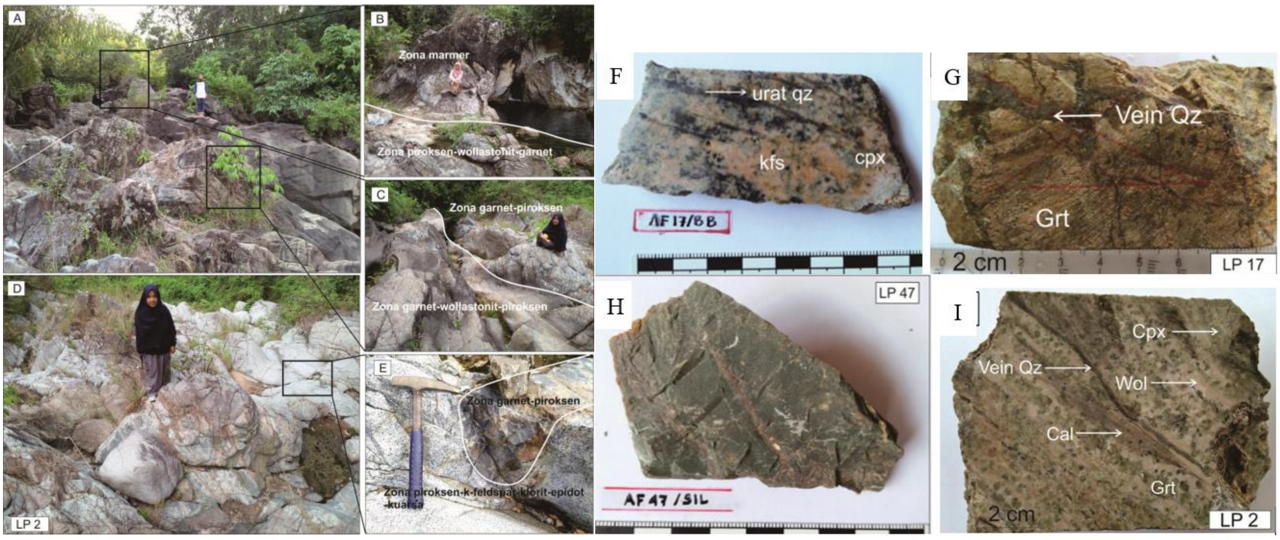


Figure 3. (A). Photo of Outcrop Contact between granodiorite and marble, (B). Contact between marble zone and garnet-wollastonite-pyroxene zone, (C). Contact between garnet-pyroxene zone and garnet-wollastonite-pyroxene zone, (D)(E). Contact between garnet-pyroxene zone and pyroxene-k-feldspar-chlorite-epidote Alteration.

A. Mineral Paragenesis

The process of skarn alteration and mineralization formation in the research area is divided into four stages, namely isochemical metamorphism, prograde skarn, retrograde skarn, and supergene enrichment (Table 1). The determination of mineral paragenesis was carried out by combining petrographic and mineragraphic analysis in the garnet-pyroxene alteration zone, garnet-pyroxene-wollastonite alteration zone, pyroxene-quartz ± epidote ± chorite alteration zone, and pyroxene-k-feldspar-chlorite-epidote alteration zone.

Isochemical metamorphic stage

During this stage, heat is added to the intrusive carbonate rock, forming marble. This heat-induced recrystallization of calcite results in an interlocking texture and abundant presence (Figure 4).

Prograde skarn

Prograde skarn consists of minerals formed at high temperatures, present in the intrusive body (endoskarn) and in the surrounding rocks (exoskarn). Pyroxene, potassium feldspar, quartz, epidote, and chlorite are found in the intrusive rock as endoskarn (Figure 3E). Epidote and chlorite appear later in the retrograde stage, replacing the pyroxene minerals. Garnet, pyroxene, wollastonite, and quartz are found in the exoskarn (Figures 5 and 10). Mineralization associated with this zone includes chalcopyrite, magnetite, and pyrite, some of which are found along with quartz. Chalcopyrite, magnetite, and pyrite are also present in smaller abundances (Figures 7, 9, and 11).

Retrograde skarn

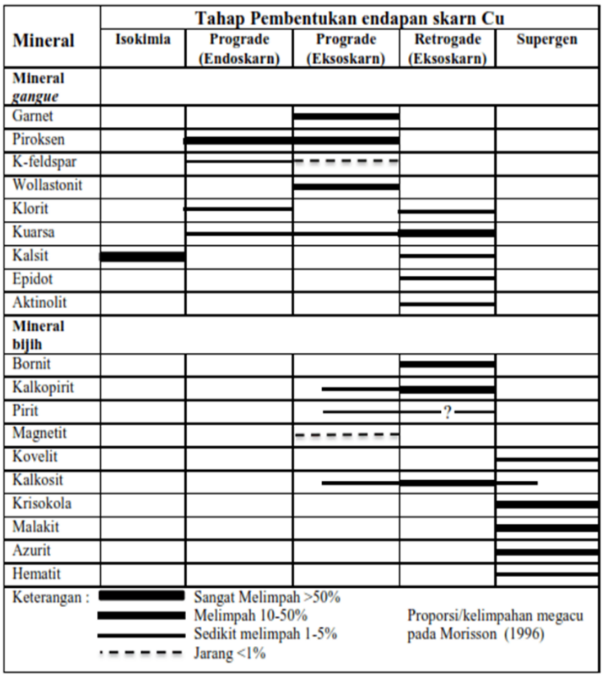
Retrograde skarn forms at lower temperatures after the mineral formation in the prograde stage has occurred. The presence of retrograde skarn is characterized by the appearance of epidote, actinolite, and calcite veins overlapping with garnet and pyroxene minerals locally (Figures 6, 8, and 10). Mineralization formed at this stage consists of chalcocite, bornite, and chalcopyrite, present with calcite and epidote veins that cut quartz veins, while bornite is present replacing wollastonite (Figure 9).

Supergene

Supergene minerals form in the final phase due to the leaching of primary mineralization by meteoric water near the surface. The supergene enrichment zone is characterized by the presence of azurite, malachite, chrysocola, covellite, and chalcocite in the form of veins and filling fractures in the preceding minerals (Figures 12 and 13).

Similar findings have been found in other locations. Research on skarn deposits in Ruwai, Central Kalimantan, shows a paragenesis pattern divided into two stages: prograde minerals characterized by the presence of quartz, and retrograde minerals characterized by chlorite and calcite [10]. Studies of skarn deposits in the Azegour area, Morocco, also highlight the paragenesis of skarn minerals based on mineral composition and fluid inclusion data. The early prograde stage is dominated by andradite and diopside under oxidative conditions, while the late prograde stage is characterized by grossular and hedenbergite formed in a reducing environment. In the retrograde stage, hydrous minerals such as chlorite, muscovite, and epidote appear along with the precipitation of sulfide minerals, marking the entry of surface or meteoritic fluids into the system [21].

Tabel 1. Paragenesis of skarn deposit minerals



V. Conclusion

A. Summary

Based on the secondary mineral assemblage, alteration in the Cu skarn deposits of the Sulita Air area can be grouped into four alteration zones: garnet-pyroxene alteration, garnet-pyroxene-wollastonite alteration, and pyroxene-quartz ± epidote ± chorite alteration, which are part of the exoskarn, and pyroxene-kJ-feldspar-chlorite-epidote alteration, which is part of the endoskarn. Skarn alteration and mineralization in the study area are divided into four stages: isochemical metamorphism, prograde skarn, retrograde skarn, and supergene enrichment. The dominant mineralization in the study area is bornite, covellite, chalcopyrite, and covellite. Chalcopyrite mineralization occurs in the prograde skarn stage after isochemical metamorphism in the garnet-pyroxene alteration, filling fractures and interstices between garnet grains along with quartz veins. Chalcopyrite-pyrite mineralization also appears in this pyroxene-quartz alteration phase. Retrograde mineralization is dominated by bornite, chalcocite, and chalcopyrite, along with cascite and epidote veins that intersect the garnet-pyroxene-wollastonite alteration zone. The final phase is characterized by a supergene process characterized by the appearance of chalcocite, covellite, hematite, malachite, azurite, and chrysocola mineralization.

B. Suggestion

To achieve a more comprehensive understanding of mineral paragenesis, it is recommended that further research be supplemented with fluid inclusion analysis and mineral chemistry. Fluid inclusion analysis can provide important information regarding the temperature, pressure, and composition of hydrothermal fluids that play a role in mineral formation, thus reconstructing the physical-chemical conditions during the mineralization process. Meanwhile, mineral chemistry analysis (for example, using the EPMA method) can identify variations in the composition of major and trace elements in minerals, which can be used to trace fluid evolution and the metasomatic processes that occurred. The combination of these two analyses will be very helpful in developing a more accurate genetic model of the deposit and supporting a scientific and in-depth interpretation of mineral paragenesis.

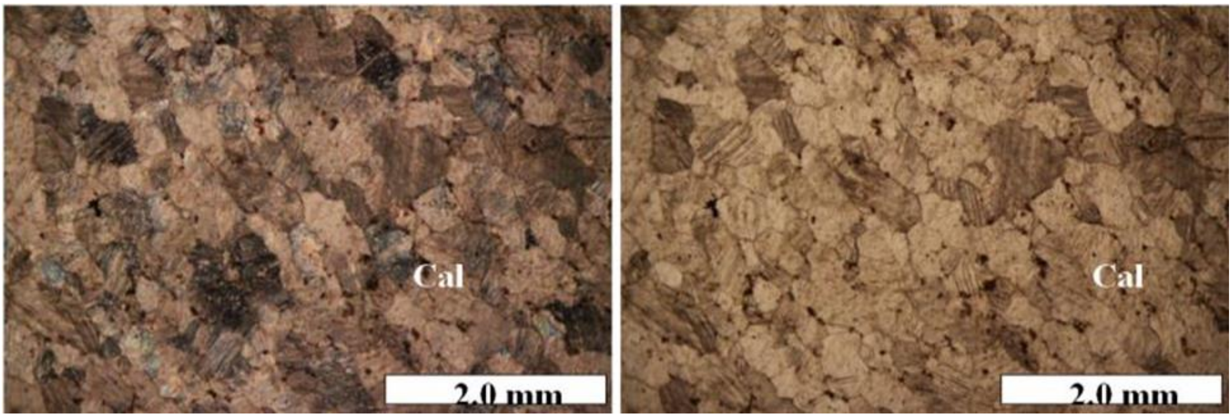


Figure 4. Thin section of AF 90/BTGP marble lithology, calcite showing interlocking structure, Cal= calcite.

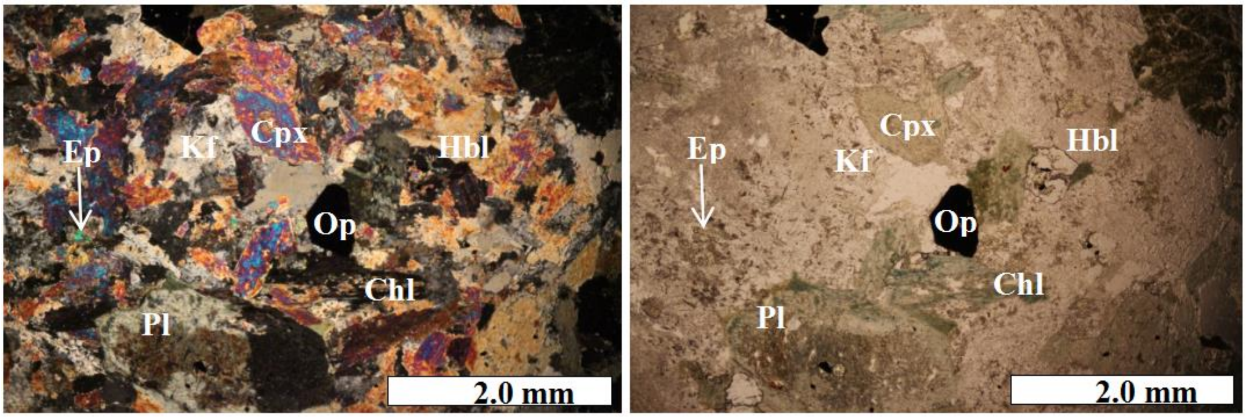


Figure 5. Thin section of granodiorite undergoing moderate endoskarn alteration in sample AF 2.1 GRD, cross-polarization appearance (left) and parallel polarization (right), local pyroxene minerals are replaced by epidote and chlorite, Cpx = Clinopyroxene, Ep = Epidote, Chl = Chlorite, Hbl = Hornblend, Kf = K-Feldspar, Pl = Plagioclase.

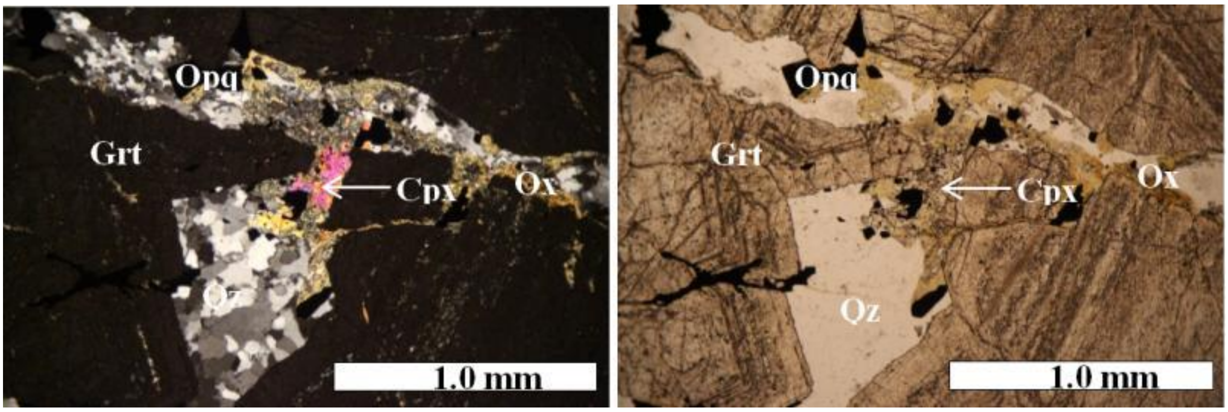


Figure 6. Thin section of sample LI 17.2 Mar, garnet-pyroxene alteration cut by quartz veins containing ore minerals, cross-polarization (left) and parallel polarization (right) appearance, Cpx = clinopyroxene, Grt = garnet, Opq = opaque mineral, Ox = oxide mineral.

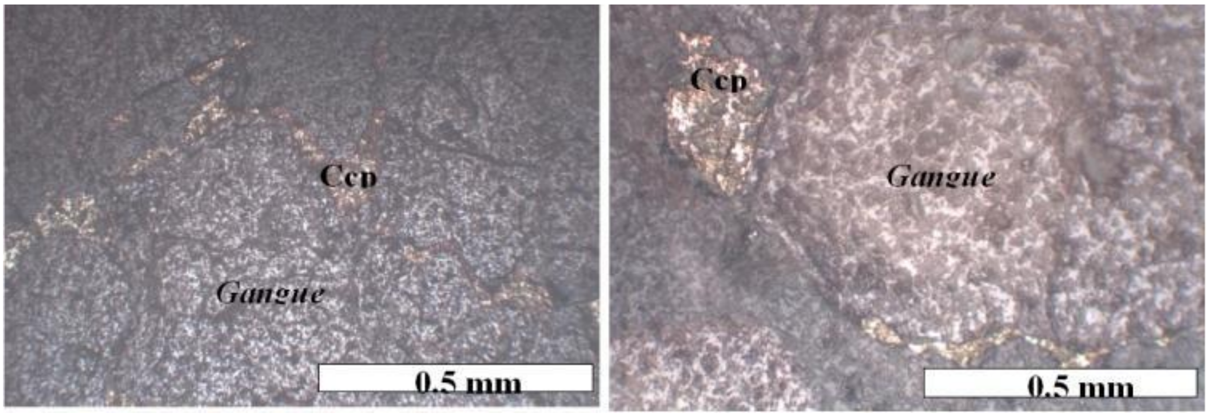


Figure 7. Polished section of sample LI 17.2 Mar, in garnet-pyroxene alteration with chalcopyrite mineralization filling fractures in the garnet. Ccp = chalcopyrite.

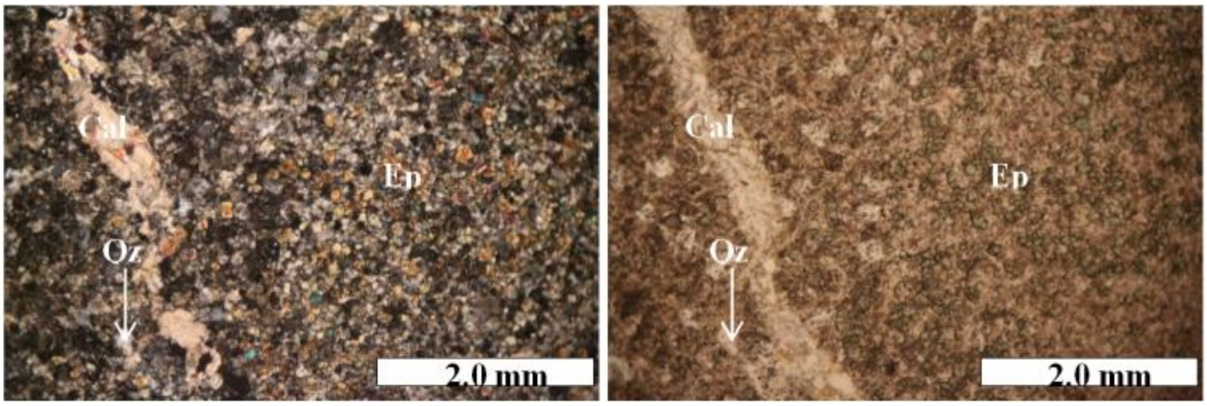


Figure 8. AF 49.2 AND pyroxene-quartz±epidote alteration section cut by barren calcite veins, cross-polarization (left) and parallel polarization (right) appearance, Cpx = clinopyroxene, Qz = quartz, Cal = calcite, Ep = epidote.

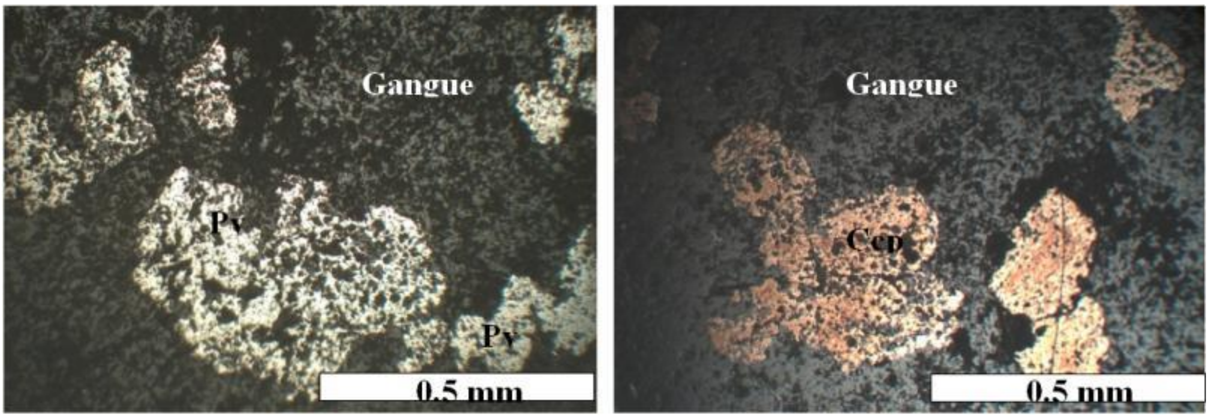


Figure 9. Photomicrograph of a polished section of LI 49.2 AND with pyrite and chalcopyrite mineralization. Note: Py = pyrite, Ccp = chalcopyrite.

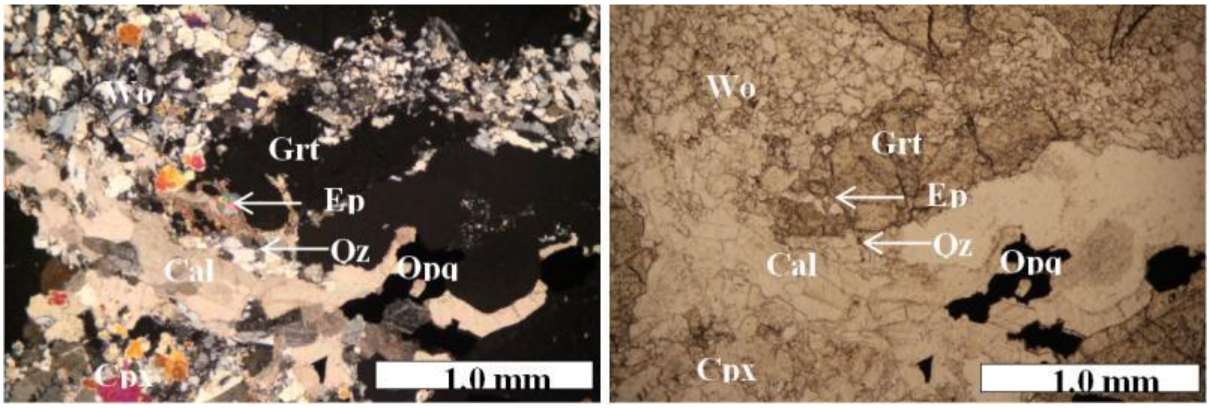
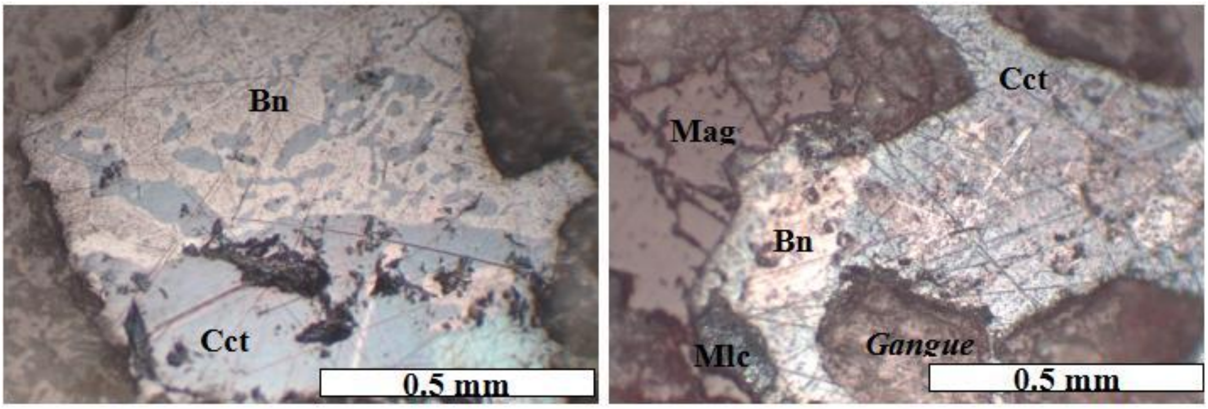


Figure 10. Thin section of sample LI 2/ MAR, garnet-pyroxene-wollastonite alteration cut by calcite veins containing ore minerals and epidote minerals, cross-polarization appearance (left) and parallel polarization (right), Cpx = clinopyroxene, Grt = garnet, Opq = opaque minerals, Ox = oxide minerals



Gambar 11. Photomicrograph of polished section LI 8.4 MAR, with chalcocite, bornite and magnetite mineralization in garnet-pyroxene-wollastonite alteration. Note: Cct = chalcocite.

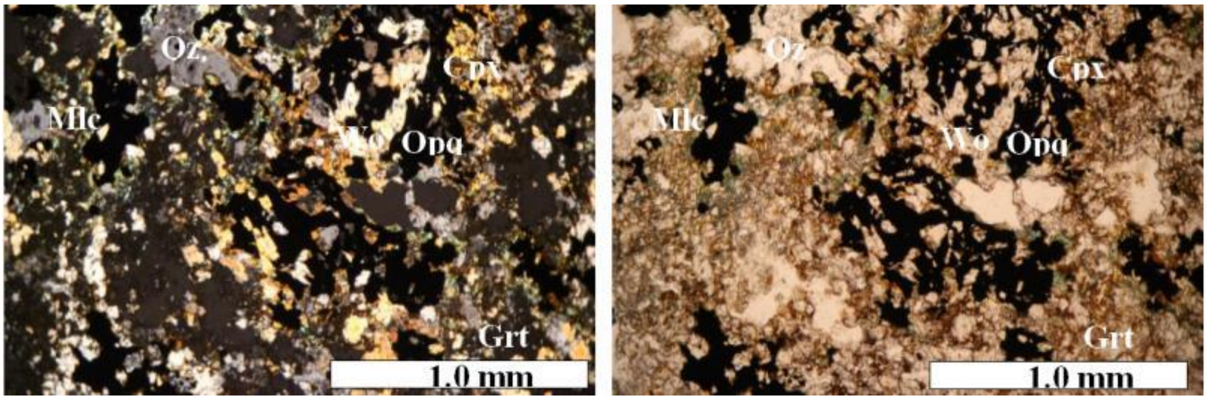


Figure 12. Thin section of sample LI 40 MAR, garnet-pyroxene-wollastonite alteration with the presence of malachite in the supergene stage replacing clinopyroxene, cross-polarization appearance (left) and parallel polarization (right), Cpx = clinopyroxene, Grt = garnet, Opq = opaque mineral, Mlc = malachite, Wo = Wollastonite.

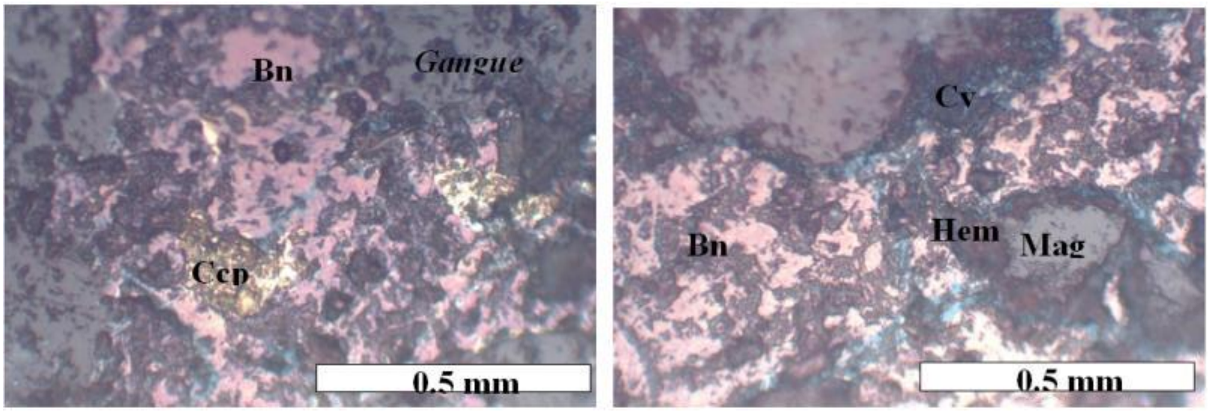


Figure 13. Photomicrograph of polished section of LI 40 MAR with bornite, chalcopyrite, magnetite, hematite and covellite mineralization. Covellite and hematite replace bornite and magnetite. Note: Bn = bornite, Cv = covellite, Mag = Magnetite, Ccp = chalcopyrite, Hem = hematite.

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