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STUDY OF ORE MINERALIZATION POTENTIAL IN METAMORPHIC ROCKS IN KAWATUNA AREA, PALU CITY, CENTRAL SULAWESI

STUDI POTENSI MINERALISASI BIJIH PADA BATUAN METAMORF DI DAERAH KAWATUNA KOTA PALU SULAWESI TENGAH

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Abstract. The Kawatuna area has a complex geological structure and lithological condition of metamorphic rock, which is estimated to be a weak zone for hydrothermal solutions to rise and then accumulate as mineralization of veins in the metamorphic rock. Based on this, it makes this area interesting to research. This research aims to identify metal ore minerals and the mineralization characteristics of ores in the research area. The method used is a geological survey of the surface and laboratory analysis through ore microscopic as well as mineral chemistry tests. Based on the results of the research study, it was found that in metamorphic rocks in the Kawatuna area, sulfide metal ore minerals were found including argentite (Ag_2S), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), and covelite minerals (CuS), Native elements ore minerals include gold (Au), silver (Ag), electrum (Au, Ag), and Oxide ore minerals in the form of hematite (Fe_2O_3). The mineralization formed is controlled by structures that produce fractures in the rock, which then produces mineralization as the veins of metamorphic rocks. The ore mineralization in the research area occurs through a hypogene process (the formation of a formation zone from primary ore minerals) and a supergene process stage (the formation of a formation or enrichment zone from secondary ore minerals)

Abstrak. *Daerah Kawatuna memiliki struktur geologi dan kondisi litologi batuan metamorf yang kompleks, yang diperkirakan merupakan zona lemah bagi larutan hidrotermal untuk naik dan selanjutnya terakumulasi sebagai mineralisasi urat-urat pada batuan metamorf tersebut. Berdasarkan hal tersebut, menjadikan daerah ini menarik untuk diteliti. Penelitian ini bertujuan untuk mengidentifikasi mineral-mineral bijih* *logam dan karakteristik mineralisasi bijih-bijih di daerah penelitian. Metode yang digunakan adalah survei geologi permukaan dan analisis laboratorium melalui uji mikroskopis bijih serta kimia mineral. Berdasarkan hasil kajian penelitian, diketahui bahwa pada batuan metamorf di daerah Kawatuna ditemukan mineral-mineral bijih logam sulfida meliputi argentit (Ag_2S), pirit (FeS_2), kalkopirit ($CuFeS_2$), sfalerit (ZnS), galena (PbS), dan mineral-mineral kovelit (CuS), mineral-mineral bijih unsur asli meliputi emas (Au), perak (Ag), elektrum (Au, Ag), dan mineral-mineral bijih oksida berupa hematit (Fe_2O_3). Mineralisasi yang terbentuk dikontrol oleh struktur yang menghasilkan rekahan pada batuan, yang kemudian menghasilkan mineralisasi sebagai urat batuan metamorf. Mineralisasi bijih di daerah penelitian terjadi melalui proses hipogene (pembentukan zona formasi dari mineral bijih primer) dan tahap proses supergene (pembentukan zona formasi atau pengayaan dari mineral bijih sekunder).*

1. INTRODUCTION

The currently global society is highly dependent on mineral commodities to meet its living needs, especially in the use of minerals as raw materials in various industrial sectors (Sukandarrumidi, 2009). Fulfillment of life's needs and very significant technological developments require the availability of raw materials in large quantities, including metal minerals (Maulana, 2020). Indonesia, including Sulawesi, has very complex geological conditions, making this area have abundant geological resources, especially metal minerals (Idrus et al., 2011; Leewen & Pieters, 2012; Maulana et al., 2020).

Mineral deposit exploration activities are carried out to reveal the potential of mineral resources, especially metal minerals (Maulana, 2020). Investigations on the potential for metal mineralization in Central Sulawesi have been widely conducted, both by Indonesian and foreign geologists, but have not yet been able to fully reveal the potential of mineral resources.

One of the areas that has the potential for mineral deposits in Central Sulawesi is in Poboya, which is a mining concession area of PT Citra Palu Mineral, with mineral-bearing rocks in the form of metamorphic rocks (Leewen & Pieters, 2012; Wajdi et al., 2012; Syafrizal et al., 2020). The similar metamorphic rock complex as the potential area also extends to the Kawatuna area, which is located to the south of Poboya. Therefore, exploration is needed through a study of the identification ore mineralization in order to reveal the potential for metal mineral resources within the locality.

This research is intended to obtain a study of the potential for ore mineralization in the research area. This study aims to identify the presence of ore minerals and characterize ore mineralization that occurs in metamorphic rocks in the research area.

2. LITERATURE REVIEW

Mineralogy is the science that discusses minerals, which are part of the material found in nature. The part that discusses the physical properties of minerals is covered by physical mineralogy, while chemical mineralogy discusses about the chemical composition of minerals. In line with the development of science and technology, currently sciences related to mineralogy have emerged, namely optical mineralogy and X-ray mineralogy (Sukandarrumidi et al., 2017). The both of them have an important role in determining the minerals constituent of rocks. Identification of minerals by geologists can be done through megascopy analysis, petrography (optical mineralogy) or analysis of X-ray patterns (Soetoto, 2013).

Megascopically mineral identification is carried out by observing the physical mineralogy of minerals in rocks. Find out the properties of a mineral is very necessary in recognizing and determining minerals macroscopically, without the support of a microscope. The physical properties required for determination are color, luster, streak, cleavage, fracture, hardness, magnetism and electricity (Sukandarrumidi et al., 2017). Sukandarrumidi et al., (2015) explains that to find out the detailed composition of minerals, this can be done by identifying the optical properties through thin sections using a polarizing microscope. This method is known as petrographic examination. Trough this method, geologists can find out in more detail the types of minerals in the rocks being examined, then geologists can find out the chemical composition and can analyze the geological processes that have occurred in the rocks, including the possibility of finding mineral resources. Petrographic studies on this thin section provide information on the minerals transparent that constituent of the rocks bearing-ore minerals. In order to observe the ore minerals (opaque minerals), related to the identification of the texture and structure of the ore that provide clues to the direction of ore mineralization (conditions, processes, and sequence of formation) polished sections are used. Polished section is a sample of rock that has had one or more surfaces flattened, then a mold made using "Transoptic Powder" (Handayani, 2015).

Identification of the element content and grade of important minerals of rocks constituent can be done using X-ray Fluorescence (XRF). This technique is effective in analyzing the chemical composition of elements to show the major and minor elements in rocks (Sabri, 2020).

3. METHODS

The study of the potential ore mineralization in the research was conducted through observation of surface geological conditions and analyzing samples in the laboratory to reveal the potential for ore mineralization that occurs in metamorphic rocks. The research method comprises data acquisition in the field and laboratory-based analysis, the findings from both will be integrated to fulfill the research objectives.

3.1. Observation of Surface Geological Conditions

Observations were carried out to obtain the data on surface geological conditions in the research area. Field observations were carried out in the form of surface geological surveys on a number of lithological outcrops, structures and characteristics of the rocks mineralized in the field. The information obtained becomes field data (in the form of descriptive notes of geological conditions and observation point coordinates). In addition, representative samples were also taken for laboratory analysis. The data of surface geological conditions in the study area includes a review of geological aspects in the form of morphology, lithology and structural appearance of rocks related to mineralization in the research area.

3.2. Sample Analysis in the Laboratory

The results of observations through surface geological surveys are then correlated with the results of laboratory data analysis of rock samples indicated to contain ore from the field. Out of several field-collected samples, five representative ones were chosen based on their mineralization, specifically the presence of veins in the sampled rock. The materials and equipment used in this laboratory analysis depend on the type or method of analysis. The following explains the methods used in sample analysis in percent to ppm concentrations.

3.2.1. Petrographic Analysis

This analysis is a microscopic rock analysis, to identify minerals in thin sections using a polarizing microscope. For this purpose, rock samples were selected which macroscopically appeared fresh or weathering haven't experienced it yet. This analysis is carried out to reveal microscopic information on the texture, structure and mineral composition of rocks to determine the name of the rock bearing-ore minerals which refers to the rock classification. This analysis was carried out on rock samples obtained from the outcrops of surface rock in the field.

3.2.2. Analysis Microscopic of Ore

Analysis is carried out by observing polished sections of the ore under a microscope to determine the type of ore mineral. The samples used for this analysis are vein samples in the rocks bearing-mineral that are indicated to have experienced mineralization. This analysis is useful for determining the types of ore minerals (metals), whether in the form of native elements or compounds (sulfides, oxides, etc.).

3.2.3. X-Ray Analysis

This analysis is needed to determine the type of element of metal minerals that are not identified using a microscope (petrography and ore microscopy), especially in the type of mineral or metal ore element. X-ray analysis using XRF to obtain mineral elements contained in the ore. This analysis technique is generally used for efficiently analysis of the constituent elements of a material/rock, because it requires a relatively small sample quantity, with a mass of around 1 gram. The main elements that are dominant in rocks bearing-ore or minerals can be detected using this analysis.

4. RESULTS AND DISCUSSION

Based on field surveys and rock sampling as well as literature studies conducted, information was obtained regarding geological conditions and ore mineralization in the study area. The following is a description of the results.

4.1. Geological Conditions of the Study Area

Physiographically, the research area is included in the physiography of Central Sulawesi. Based on the physiography, Sulawesi has a wedge-shaped (Bemmelen, 1949). In terms of geomorphology, the study area in the Palu city area has regional morphological units in the form of plains, denudation hills and fault cliff mountains (Sukamto, 1973). The morphology of the plains has an irregular topographic appearance, is a seasonally flood area with material composed of alluvial deposits from rivers and shore. The morphology of denudation hills is shown by the wavy morphological appearance, and has several alluvial fans. The morphology of mountains occupied areas with higher elevations, generally characterized by the appearance of steep cliffs and the appearance of the morphological straightness (lineament) due to the fault process.

The regional stratigraphy of the research area includes a metamorphic rock complex consisting of schist, gneiss and marble rock units (Sukamto, 1973). The regional structure of the research area is be effected by the Palu-Koro active fault zone which is relatively North-Northwest oriented, with the appearance of morphological straightness (lineament) and the presence of faults and fractures in the rocks along the active fault zone (Sukamto, 1973). The appearance of faults and lineaments that appear dominantly along the eastern ridge of the Palu Valley, where the research location is located.

The results of the surface geological survey describe the geological conditions of the research area, including lithology and structural appearance of the rocks. Based on observations and survey in the field, it can be seen that the research area is dominated by metamorphic rocks in the form of schist and gneiss units, and some contain granodiorite rocks and also deposits of sand-boulder size (**Figure 1**).

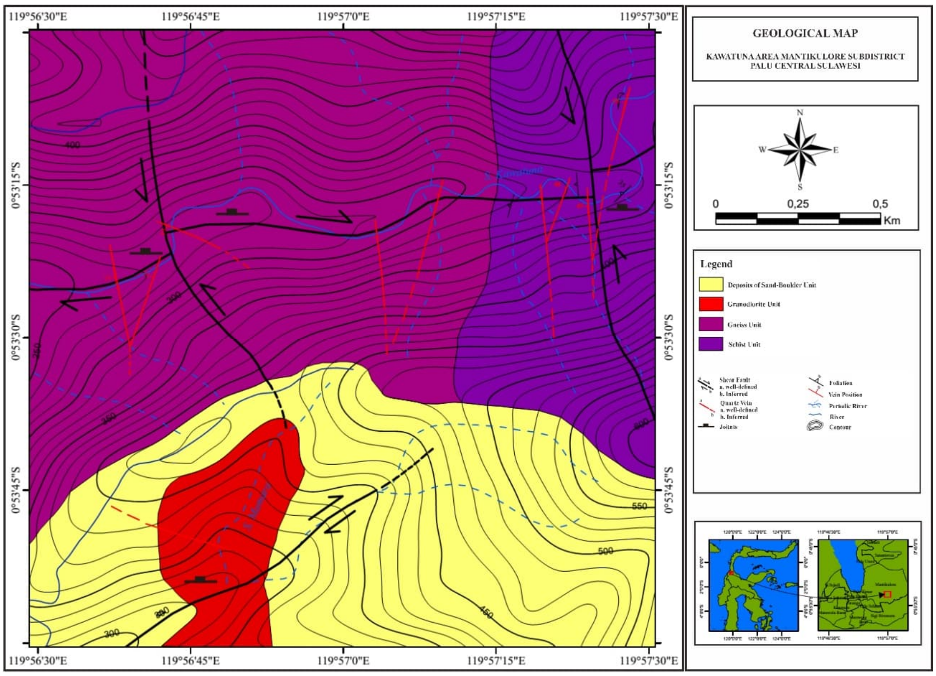

Figure 1. Geological Map of Research Area.

Schist lithology, a metamorphic rock type, occurs in the eastern part of the study area. This rock is characterized macroscopically by a gray color in its fresh state and a brownish color when weathered, a nematoblastic texture, and a schistosic structure. Microscopic observation through petrographic analysis of thin sections from field samples reveals physical characteristics showing whitish-brown color under plane-polarized light (PPL) and dark gray color under crossed-polarized light (XPL). The mineral shapes are subhedral to anhedral, with grain sizes ranging from < 0.1 mm to 0.5 mm, and the mineral composition includes Quartz, Muscovite, Biotite, Actinolite, and Sericite (**Figure 2**).

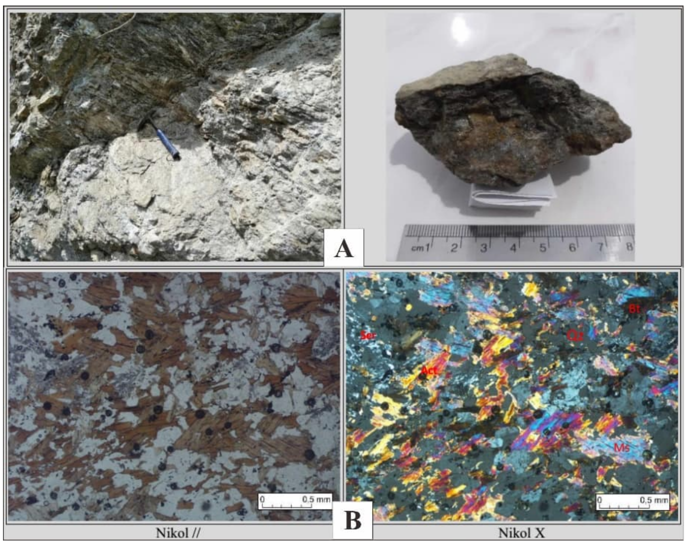

Figure 2. Schist Lithology of the Study Area; A. Macroscopic Appearance, and B. Photomicrograph of a thin section showing the presence of Quartz (Qz), Muscovite (Ms), Biotite (Bt), Actinolite (Act), and Sericite (Ser).

Another metamorphic rock encountered in the study area is the Gneiss Unit. This unit is distributed from the northwest to the west of the study area, predominantly occupying it. Macroscopically, this unit exhibits a gray color in fresh conditions and brownish in weathered conditions in the field, displaying a granoblastic texture and gneissic structure. Microscopic observation from petrographic analysis of thin sections reveals physical characteristics showing whitish-brown color under plane-polarized light (PPL) and dark gray color under crossed-polarized light (XPL). The mineral shapes are subhedral to anhedral, with grain sizes ranging from < 0.1 mm to 0.5 mm, and the mineral composition includes Quartz, Feldspar, Actinolite, Chlorite, and Clay minerals (**Figure 3**).

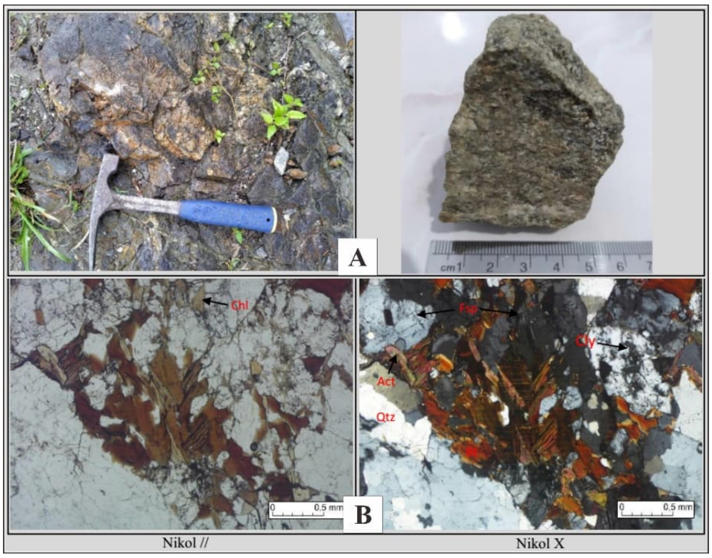

Figure 3. Gneiss Lithology of the Study Area; A. Macroscopic Appearance, and B. Photomicrograph of a thin section showing the presence of Quartz (Qz), Feldspar (Fsp), Actinolite (Act), Chlorite (Chl), and Clay minerals (Cly).

The Granodiorite Lithology is distributed in the southwest part of the study area. Macroscopically, this unit exhibits a whitish-gray color in fresh conditions and a brownish-gray color in weathered conditions in the field, displaying a phaneritic texture and massive structure. Microscopic observation from petrographic analysis of thin sections reveals physical characteristics showing a whitish-brown color under plane-polarized light (PPL) and a dark gray color under crossed-polarized light (XPL). The mineral shapes are subhedral to anhedral, with grain sizes ranging from 0.1 mm to 0.5 mm, and the mineral composition includes Quartz, Plagioclase, and Biotite (**Figure 4**).

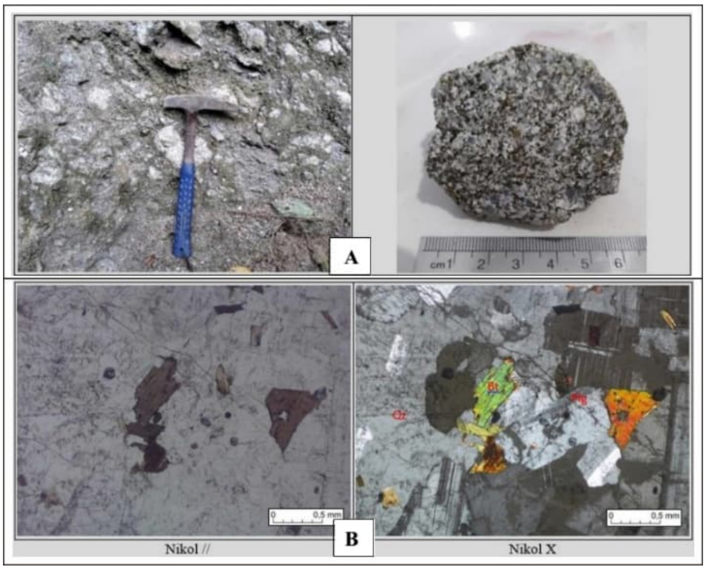

Figure 4. Granodiorite Lithology of the Study Area; A. Macroscopic Appearance, and B. Photomicrograph of a thin section showing the presence of Quartz (Qz), Plagioclase (Pl), and Biotite (Bt).

The Sand-Boulder Deposit exhibits an unconformable relationship with the granodiorite unit and is distributed in the southwest to southeast parts of the study area. This unit is composed of reworked material from older rock formations, consisting of conglomerate, sand, and also granitoid boulders, all of which are poorly consolidated. Megascopically, the outcrop generally appears brownish in color and displays an upward-fining grain size gradation, ranging from sand to boulders (**Figure 5**).

Figure 5. The appearance of the alluvial deposit consists of reworked material ranging in size from sand to boulders.

Field observation and data analysis yielded information on the presence of structures such as joints, fault breccia, fault planes, and slickensides. Identification through joint analysis indicates that shear joints and strike-slip faults are present as developed geological structures in the study area.

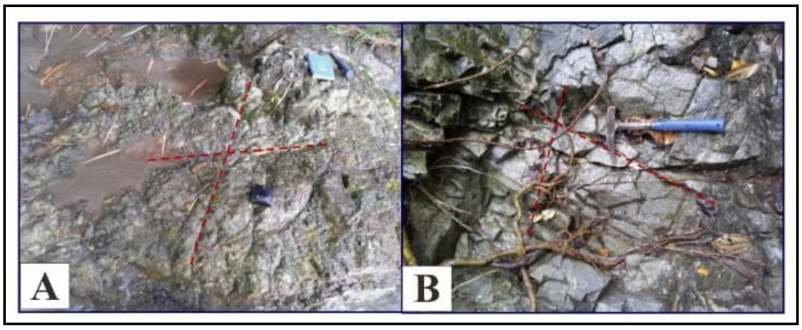

Figure 6. The appearance of structural features (fractures/joints) in the metamorphic rocks of the study area; A. Fractures in Gneiss and B. Fractures in Schist.

Shear fractures are observed pervasively within the metamorphic rocks of the study area (**Figure 6**), This is attributed to the significant structural control exerted by a major structure, the Palu Koro Fault, within the study area. The observed fractures consist of both systematic and non-systematic shear fractures. Some fractures are filled with silica minerals, forming stockworks, while others lack infill. Vein orientations, based on attitude measurements projected onto a stereographic projection (**Figure 7**), reveal a general trend of Northwest–Southeast (N173°E/73°) and Northeast–Southwest (N185°E/44°).

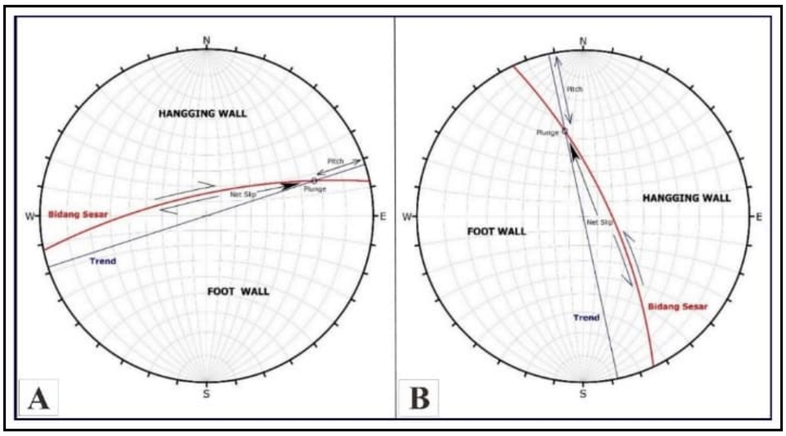

Figure 7. Projection results of fault structure data on (A) Gneiss and (B) Schist.

4.2. Ore Mineralization of the Study Area

Mineralization within the study area is characterized by the presence of veins occupying fractures in the metamorphic rocks, exhibiting a variety of orientation trends. Generally, the distribution of veins in the study area shows a dominant orientation trending Northwest – Southeast (NW-SE) and Northeast – Southwest (NE-SW). The orientation of veins is commonly strongly influenced by the geometry and distribution of fractures present within the study area. These veins, which represent fractures filled with quartz (although some veins indicate an association of silica-carbonate), were generally formed by compressional and tensional forces and are observed in almost all lithological units, particularly the metamorphic rocks of schist and gneiss. Mineralization in the study area is manifested in the form of these veins. Within these veins, economically valuable ore minerals can be concentrated and associated with gangue minerals. Additionally, mineralization can also occur in the host rocks that have undergone contact with hydrothermal solutions. Ore mineralization identification through mineragraphic analysis (**Figure 8**) reveals the presence of diverse ore minerals, including argentite (Ag_2S), gold (Au), silver (Ag), electrum (Au, Ag), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), and covellite (CuS).

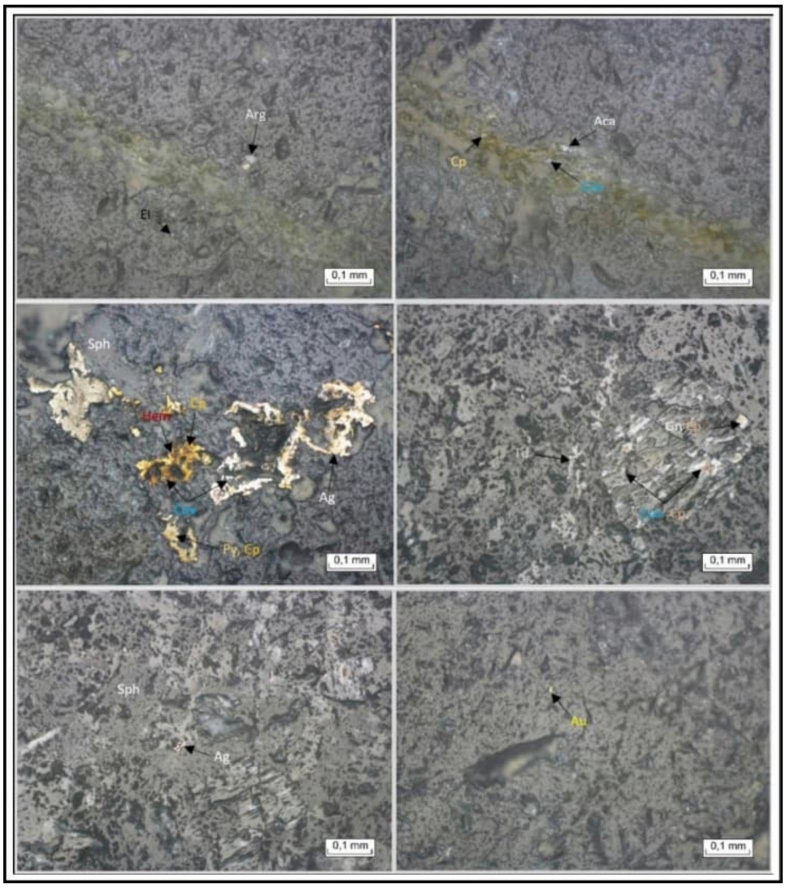

Figure 8. Photomicrographs from the polished sections of quartz veins from the study area showing the presence of ore minerals Argentite (Arg), Electrum (El), Chalcopyrite (Cp), Covellite (Cov), Sphalerite (Sph), Pyrite (Py), Chalcopyrite (Cp), Galena (Gn), Hematite (Hem), Silver (Ag), and Gold (Au).

Identification through chemical element analysis of minerals from veins within the metamorphic rocks of the study area reveals the presence of metal elements with varying concentrations. The presence of chemical elements in vein samples collected from the field confirms the occurrence of concentrated metallic ore minerals within the veins as a product of mineralization. The results of XRF analysis on vein samples from the study area are presented in **Table 1**.

Table 1. Chemical Element Data from XRF Analysis of Vein Samples from the Study Area

No.	Element	Unit	Elements Concentration from Sample					annotation
			STA.02	STA.05	STA.07	STA.10	STA.11	
1	Si	%	36.563	65.267	69.952	83.688	62.339	*bdl = below detection limit*
2	Al	%	18.995	10.944	11.813	5.218	3.137	

No.	Element	Unit	Elements Concentration from Sample					annotation
			STA.02	STA.05	STA.07	STA.10	STA.11	
3	Fe	%	19.544	2.48	6.87	4.344	5.78	
4	K	%	5.71	4.2	3.51	4.112	1.569	
5	Ca	%	11.745	15.864	4.753	1.317	26.129	
6	Mg	%	2.845	0.654	1.564	0.329	0.251	
7	Ti	%	3.134	0.04	0.666	0.382	0.176	
8	Cl	%	0.163	0.002	0.097	0.166	0.048	
9	S	%	0.071	0.1	0.115	0.135	0.093	
10	Ba	%	0.081	0.043	bdl	0.092	bdl	
11	Mn	%	0.213	0.147	0.376	0.038	0.18	
12	Sn	%	0.028	0.023	0.028	0.031	0.048	
13	Te	%	0.024	0.021	0.026	0.029	0.044	
14	Sr	%	0.355	0.159	0.05	0.02	0.078	
15	Eu	%	0.104	0.016	0.072	0.017	0.043	
16	Rb	%	0.035	0.004	0.01	0.018	0.016	
17	Cr	%	0.067	0.001	0.01	0.011	0.007	
18	Sb	%	bdl	0.007	0.009	0.011	0.015	
19	Zr	%	0.124	0.001	0.011	0.01	0.005	
20	Zn	%	0.062	0.007	0.012	0.01	0.013	
21	V	%	0.05	0.007	0.023	0.008	0.011	
22	Ni	%	0.016	0.005	0.006	0.014	bdl	
23	Cu	%	0.012	0.004	0.012	0.003	0.003	
24	Pb	%	0.009	0.001	0.004	0.002	bdl	
25	Yb	%	0.011	0.001	0.002	0.001	0.005	
26	Y	%	0.014	0.001	0.004	0.001	0.007	
27	Ga	%	0.012	bdl	0.003	0.001	bdl	
28	Nb	%	0.005	bdl	bdl	bdl	bdl	
29	As	%	0.002	bdl	0.001	bdl	bdl	
30	Th	%	0.007	bdl	bdl	bdl	bdl	
31	Re	ppm	bdl	0.5	1	1	4.6	
32	Au	ppm	bdl	0.2	bdl	bdl	0.6	

The results of chemical element analysis (**Table 1**) using XRF on several vein samples from surface metamorphic rocks indicate that the chemical element Si (Silica) has the highest concentration within the veins, with an average grade of 63.56% per sample. The concentrations of other chemical elements consist of 11.96% Ca, 10.02% Al, 7.80% Fe, 3.82% K, and 1.13% Mg. The remaining 1.70% represents byproducts in the form of elements such as 0.4 ppm Au and 0.01 ppm Cu, along with other trace elements (**Figure 9**).

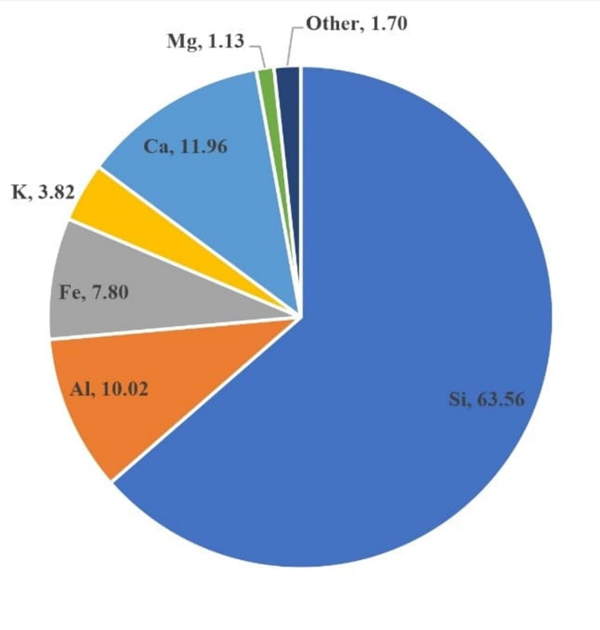

Figure 9. Elemental Distribution Diagram in Veins of the Kawatuna Metamorphic Rocks.

Based on the analyzed data described above, it can be inferred that mineralization in the metamorphic rocks is characterized by the occurrence of veins containing ore minerals. Surface geological reconnaissance indicates that vein-hosted mineralization in the rocks of the study area is closely related to the role of the Palu-Koro Fault as a major fault that triggered the development of minor faults within the research area (Assidiqi at al., 2023). The activity of these faults generated fractures/openings in the rocks, which subsequently served as pathways and accumulation sites for hydrothermal minerals deposited by hydrothermal solutions ascending towards the surface(Leewen & Pieters, 2012; Assidiqi at al., 2023). The orientation of veins in the metamorphic rocks of the Kawatuna area generally aligns with the principal stress pattern of the major fault, similar to the mineralization found in Poboya (Leewen & Pieters, 2012; Wajdi et al., 2012; Assidiqi at al., 2023), Wombo (Rahmaningrum & Asrafil, 2021), and Bora area (Marliani & Asrafil, 2021).

Ore minerals from the native element group include silver (Ag), gold (Au), and electrum (Au,Ag). These minerals are generally found in association with pyrite and chalcopyrite. Physically, these minerals are not visible to the naked eye due to their microscopic size. Through microscopic observation using ore microscope, these minerals are characterized by their colors: gold (Au) exhibits a very bright yellow, silver (Ag) displays a very bright white, and electrum (Au,Ag) shows a very bright yellowish-white. Other microscopic characteristics of these minerals include the absence of cleavage, subhedral to anhedral forms, isotropy, very high reflectivity, no bireflectance, and an infilling ore texture.

Ore minerals from the sulfide group identified microscopically include pyrite (FeS_2), argentite (Ag_2S), chalcopyrite ($CuFeS_2$), sphalerite ($(Zn,Fe)S$), galena (PbS), and covellite (CuS). These minerals occur in mutual association within veins in the metamorphic rocks. Pyrite, physically, is still macroscopically visible but with a fine grain size; it is characterized by a pale yellow color, exhibits cleavage, occurs in subhedral to anhedral forms, is isotropic, and has high reflectivity. Chalcopyrite, characterized by a yellow color, displays cleavage with anhedral forms, possesses high reflectivity, and shows weak bireflectance.

Argentite, microscopically, is characterized by a gray color, exhibits cleavage, occurs in anhedral to subhedral forms, shows bluish-gray anisotropy, has moderate reflectivity, and very weak bireflectance. Microscopic analysis indicates the presence of pyrite, chalcopyrite, and argentite in veins with a replacement ore texture. The replacement texture suggests that the ore minerals are present due to chemical composition changes from hydrothermal solutions that filled spaces within the host rocks (Morrison et al., 1990).

The ore mineral sphalerite, through microscopic analysis, exhibits a gray color, closely resembling Galena which is silver-gray. Both minerals, microscopically, are observed to possess cleavage, occur in anhedral to subhedral forms, are isotropic, have low reflectivity, show no bireflectance, and display infilling and intergrowth ore textures. Furthermore, the other sulfide mineral, covellite, shows a light blue color with cleavage and anhedral forms under microscopic analysis, exhibits red-orange anisotropy, low reflectivity, strong bireflectance, and possesses an exsolution ore texture.

Hematite (Fe_2O_3), as an oxide mineral, is present in microscopic analysis in association with chalcopyrite and pyrite. Microscopically, it appears reddish-brown in color, lacks cleavage with an anhedral form, exhibits brownish-yellow anisotropy, has moderate reflectivity, weak bireflectance, and displays a replacement ore texture.

Mineralization occurring in the Kawatuna area is indicated to involve a complex hydrothermal fluid circulation process. This process is followed by the formation of hydrothermal alteration, which is characteristic of the presence of an ore deposit (Asrafil et al., 2017; Idrus et al., 2011; Pirajno, 2019; Maulana, 2020). Hydrothermal alteration in the rocks is identified through the indicated presence of clay minerals observed megascopically in the field and microscopically in thin section of gneiss and schist samples, specifically in the form of Chlorite, Actinolite, and Sericite. Referring to the alteration types and their mineral assemblages (Corbett & Leach, 1997), the presence of alteration minerals such as chlorite and actinolite is interpreted to indicate a propylitic alteration type, while sericite suggests a phyllic alteration type.

The ore mineral formation process in the study area is interpreted to occur in two stages: hypogene and supergene. The hypogene zone represents the formation of primary ore minerals consisting of silver, sphalerite, galena, pyrite, chalcopyrite, electrum, and gold. In contrast, the supergene zone represents the formation or enrichment of secondary ore minerals consisting of argentite, covellite, and hematite.

Table 2. Paragenesis of Ore Mineralization in the Study Area.

Ore Minerals	Stage Mineralization			
	Hypogenee			Supergene
	Early	Middle	Late	
Silver (Ag)	—	—	—	
Sphalerite (ZnS)	—	—	—	
Galena (PbS)	—	—	—	
Pyrit (FeS2)	—	—	—	
Chalcopyrite (CuFeS2)		—	—	
Electrum (Au,Ag)			—	
Gold (Au)			—	
Argentite (Ag2S)				—
Covelite (CuS)				—
Hematite (Fe2O3)				—

The genesis of ore minerals, interpreted based on mineral relationships and microscopic textures, indicates that the earliest formed ore minerals are silver and sphalerite. Silver is present filling spaces between quartz veins (infilling texture). The occurrence of sphalerite, commonly associated with silver, exhibits an intergrowth ore texture. The next ore mineral to form is galena, which fills spaces between sphalerite grains. Subsequently, pyrite appears with a replacement texture, replacing silver, sphalerite, and galena, and also occurs as chalcopyrite disease within sphalerite. Following this, electrum and gold are present together, filling fractures in quartz. Covellite occurs with an exsolution texture within chalcopyrite. Argentite, covellite, and hematite are inferred to be present as minerals formed due to supergene enrichment processes. The paragenesis of mineralization from ore minerals originating from the metamorphic rocks in the study area is shown in **Table 2**.

The results of the study on surface metamorphic rocks in the research area have indicated the potential for economically valuable ore mineralization. Therefore, the research team recommends further in-depth studies integrating various methods such as geophysics, geology, and geochemistry. This is crucial for obtaining a zonation of potential ore deposits and determining the magnitude of the potential quantitatively, not only at the surface but also subsurface. It is can begin by identifying subsurface mineralization zones through a geophysical approach that integrates geoelectric resistivity, induced polarization, and Controlled Source Audio-Frequency Magnetotellurics (CSAMT) data (Rahman et al., 2017; Pertiwi & Jiwandono, 2021).

5. CONCLUSION

Based on the results of the research conducted, the following conclusions are drawn: Ore Mineralization of the Study Area: various types of metallic ore minerals were identified through ore microscopy analysis and mineral chemical tests. The ore mineral types present in the metamorphic rock veins of the study area include sulfide metallic ore minerals such as argentite (Ag_2S), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), and covellite (CuS); native element ore minerals including gold (Au), silver (Ag), and electrum (Au, Ag); and an oxide ore mineral in the form of hematite (Fe_2O_3).

Characterization of ore mineralization in the metamorphic rocks, based on a study of the surface geological conditions of the research area, microscopic analysis, and chemical testing, indicates that the mineralization is controlled by developed geological structures that formed fractures within the metamorphic rocks, serving as pathways for mineralization in the form of veins containing ore minerals. Ore mineralization in the study area occurred through hypogene and supergene processes. The hypogene zone represents the formation of primary ore minerals consisting of silver (Ag), sphalerite (ZnS), galena (PbS), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), electrum (Au, Ag), and gold (Au). In contrast, the supergene zone represents the formation or enrichment of secondary ore minerals consisting of argentite (Ag_2S), covellite (CuS), and hematite (Fe_2O_3).

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