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Article

Analysis of Mineralization in The Galena Deposit at Baturappe Village, Gowa Regency, South Sulawesi Province

Muhamad Hardin Wakila*, Alfian Nawir, Harwan, Mubdiana Arifin, Yushar Khatib Warta

Department of Mining Engineering, Faculty of Industrial Technology, Universitas Muslim Indonesia, Makassar, Indonesia

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***Corresponding author:**
wakilahardin@umi.ac.id

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ABSTRACT

Galena deposits are a mineral resource of high economic value and play a crucial role as a source of lead (Pb) in various industries. Galena deposits have been discovered in Baturappe Village, Gowa Regency, South Sulawesi Province; however, there is currently no preliminary information regarding the prospects of these galena deposits in the area. The objectives of this study are to identify the ore minerals of the galena deposits and their associated minerals, to describe the texture of the galena deposit minerals, and to determine the paragenetic sequence of the galena deposits in the study area. The research methods employed were mineragraphic and X-ray diffraction. Ore minerals in the deposits were identified as galena, pyromorphite, cerussite, and anglesite. The associated minerals are quartz, illite, pyrite, malachite, covellite, and chalcopyrite. The mineral textures observed in samples 1, 2, and 3 include: disseminated, vein/veinlet, fracture-filling, replacement, coating, and cavity-filling textures. The paragenetic stages begin with the early stage, characterized by the formation of quartz as the primary gangue mineral, followed by pyrite and chalcopyrite as primary sulfides during the hypogene stage. The subsequent stage is marked by the formation of galena as a primary sulfide that fills fractures and intergranular spaces, as well as partially replacing the previous sulfides. The final stage is marked by the formation of secondary minerals resulting from supergene enrichment (calcosite/covellite) and oxidation (malachite, anglesite, cerussite, and pyromorphite), which partially replace galena and chalcopyrite through replacement textures and coat the surfaces of the primary minerals (coating).

1. Introduction

Indonesia is located at the junction of the world's three major tectonic plates: the Eurasian, Indo-Australian, and Pacific plates. These conditions result in complex geological activity in Indonesia and the potential for various types of metal mineral deposits [1]. South Sulawesi is one region with complex geological conditions and a long tectonic history, giving it the potential to form various types of metal mineralization deposits, including sulfide minerals such as galena [2].

The Baturappe area, located in Gowa Regency, South Sulawesi Province, is known to show indications of galena mineralization found in quartz veins and hydrothermal alteration zones [3]. This mineralization is believed to be associated with hydrothermal activity influenced by geological structures such as faults and rock fractures. These structures serve as migration pathways for hydrothermal fluids that carry metal elements to mineral deposition zones [4]. The presence of hydrothermal alteration and quartz veins containing sulfide minerals indicates that this area has interesting geological potential warranting further study. An analysis of the mineralization is necessary to understand the characteristics of the galena deposit, including mineral associations, alteration types, mineralization textures, and the relationship between the mineralization and the geological conditions of the study area. Such a study is important because it can provide information on the processes of deposit formation, structural control over mineral distribution, and the potential mineral resources contained in the study area [5].

Research on galena mineralization in the Baturappe area has been relatively limited to date. Most previous studies have focused primarily on the regional geological conditions of South Sulawesi or provided only reconnaissance-

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level descriptions of base-metal occurrences, without a detailed integrated mineralogical characterization of the galena deposits [3]. Consequently, there remains a significant knowledge gap concerning the ore mineral assemblage, textural relationships, and the complete paragenetic sequence from hypogene sulfide deposition to supergene oxidation in this locality. The novelty of the present study lies in its integrated application of reflected-light ore microscopy (mineragraphy) and X-ray diffraction (XRD) to reconstruct, for the first time in the Baturappe district, the full paragenetic evolution of the galena-bearing system. This approach allows discrimination between primary hypogene sulfides and secondary supergene minerals, thereby providing a clearer genetic model of mineralization that has not been previously established for this area. Accordingly, the specific objectives of this research are: (1) to identify the ore minerals and associated gangue minerals present in the galena deposits of Baturappe Village; (2) to describe the textural characteristics of the ore minerals and interpret their genetic significance; and (3) to establish the paragenetic sequence of mineral formation from the early hypogene stage through to the final supergene oxidation stage. The results are expected to contribute fundamental data for future exploration targeting and resource evaluation of lead mineralization in South Sulawesi.

2. Research and Methodology

This study began with a comprehensive literature review on galena mineralization and related hydrothermal systems, followed by the systematic collection of three representative galena-bearing rock samples from the study area in the form of chip samples or hand specimens (Figure 1) [6], [7].



Figure 1. Sample Collection

The samples were carefully selected to represent different textural and mineralogical variations observed in the field. The rock samples were prepared into polished sections using standard ore microscopy procedures. Mineralogical observations were conducted under a reflected-light microscope to identify ore minerals, associated gangue minerals, mineral habits, grain sizes, intergrowth relationships, and mineralization textures [8]. Textural criteria including replacement, vein-filling, coating, and cavity-filling relationships were used as the primary basis for establishing the relative timing of mineral formation (paragenesis). In parallel, the samples were analyzed by X-ray diffraction (XRD) to obtain complementary mineral identification based on characteristic diffraction patterns. Diffractograms were interpreted by matching peak positions and intensities against standard mineral databases, allowing semi-quantitative estimation of relative mineral abundances [9]. The XRD results were then systematically cross-validated with the mineragraphic observations. This integrated approach enabled more reliable discrimination between primary hypogene sulfides and secondary supergene oxidation products, and provided a robust foundation for reconstructing the complete paragenetic sequence of the deposit.

3. Results and Discussion

3.1. Mineragraphic Analysis

3.1.1. Sample 1

Based on the results of the mineralogical analysis, sample 1 is dominated by galena (PbS) associated with pyrite and silica minerals (quartz). The galena is anhedral to subhedral in shape, measures 0.3-3 mm, is bright white (galena

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white) with high reflectivity, and exhibits characteristic triangular cleavage pits. Pyrite is subhedral to anhedral, bright brass-yellow in color, with high reflectivity and varying sizes. Quartz is present as an anhedral matrix filling the voids, exhibiting a banded colloform texture (Figure 2). The intermineral relationships indicate a replacement texture, in which bluish-green pyromorphite (5%) with strong internal reflections is found coating or partially replacing the galena as a result of oxidation processes during the final stage of mineralization.

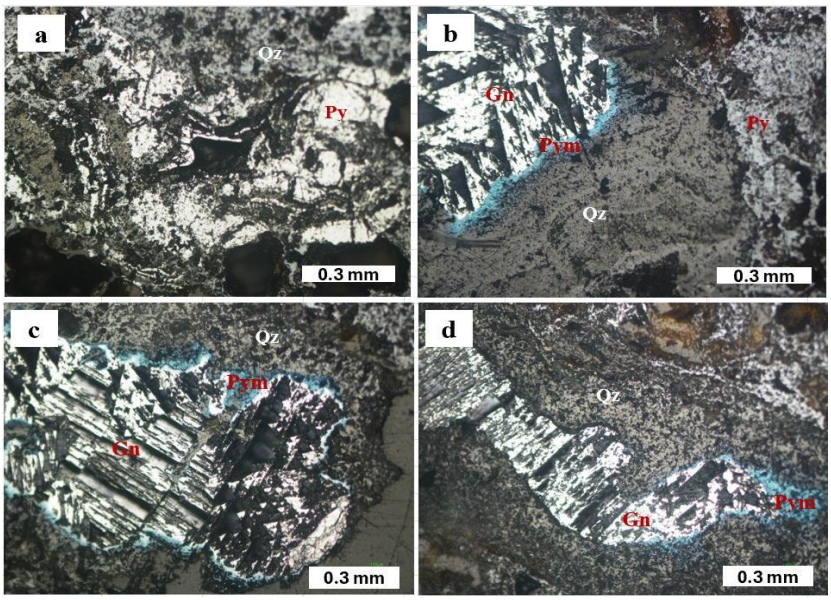


Figure 2. Photomicrograph of Sample 1

3.1.2. Sample 2

Based on the mineralogical analysis, Sample 2 is dominated by galena (PbS) associated with quartz, pyrite, malachite, and covellite. The galena is anhedral to subhedral in shape, measuring 0.3-3 mm, with a characteristic triangular cleavage, while pyrite is present in smaller proportions (5%) and is subhedral to anhedral in shape. Malachite $(Cu_2CO_3)(OH)_2$ is light green to medium green in color, anhedral in shape, ranging in size from 0.5–3 mm, and occurs as fracture-filling material. Covellite occurs in fine-grained forms, is indigo blue in color, and exhibits very strong to extreme birefringence and pleochroism. The intermineral textural relationships indicate a replacement pattern, in which malachite and covellite are secondary minerals resulting from supergene oxidation/enrichment that have replaced the primary Cu sulfide mineral (chalcopyrite).

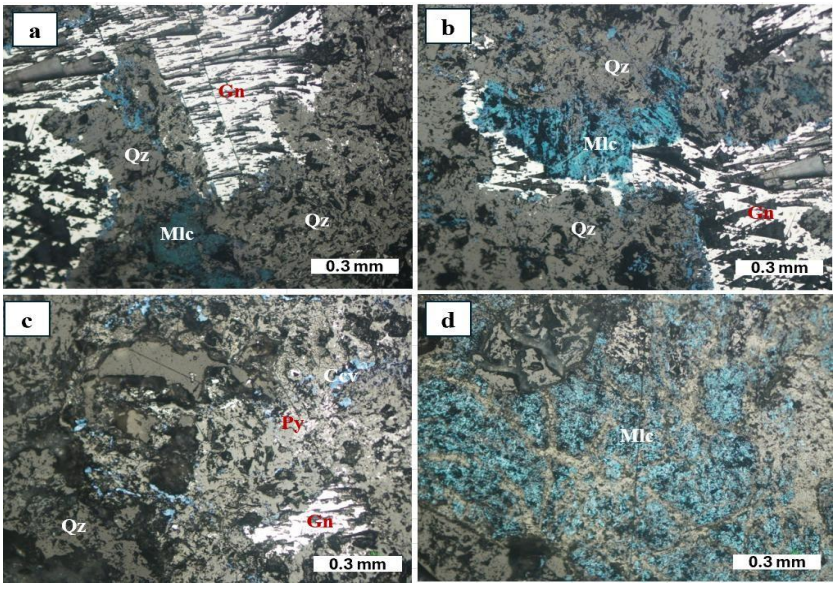


Figure 3. Photomicrograph of Sample 2

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3.1.3. Sample 3

Based on the mineralogical analysis, Sample 3 is dominated by quartz (77%) as the gangue mineral, with the ore minerals pyrite and chalcopyrite present in minor proportions. Pyrite is euhedral to subhedral (cubic in shape), measuring 0.1-3 mm, bright yellow in color with high reflectivity. Chalcopyrite ($CuFeS_2$) is anhedral, occurring as massive masses or irregular grains, fine-grained (<0.3 mm), and golden yellow in color, a shade darker than pyrite. The intermineral relationships indicate a replacement texture, meaning that chalcopyrite is found filling fractures or partially replacing pyrite, consistent with the paragenetic sequence in which chalcopyrite formed during the main hypogene stage following the precipitation of pyrite during the early hypogene stage.

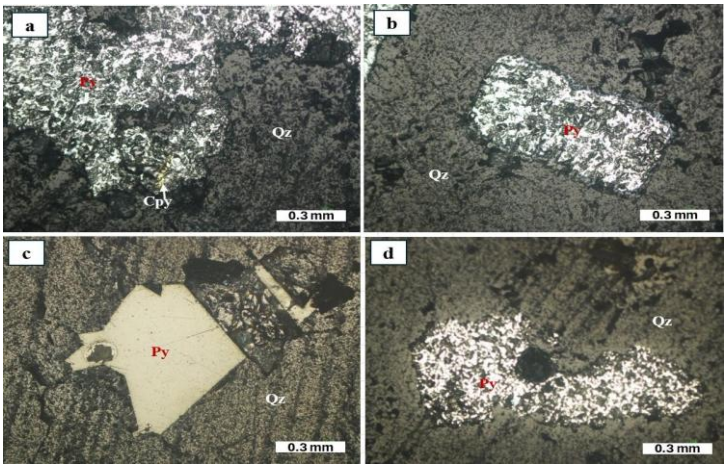


Figure 4. Photomicrograph of Sample 3

3.2. X-Ray Diffraction Analysis

3.2.1. Sample 1

The results of the XRD analysis of Sample 1 show that the rock sample is dominated by quartz (SiO_2) with a relative abundance of 49.1%, followed by illite ($Al_4K{\cdot}O_{12}Si_2$) at 41.8%. The ore minerals identified in this sample are galena (PbS) at 5.4% and cerussite ($PbCO_3$), a secondary mineral resulting from the oxidation of galena, at 3.7%. The measurement results per step are converted into a graph of intensity peaks, which is also called a diffractogram [10]. The following is the diffractogram for Sample 1.

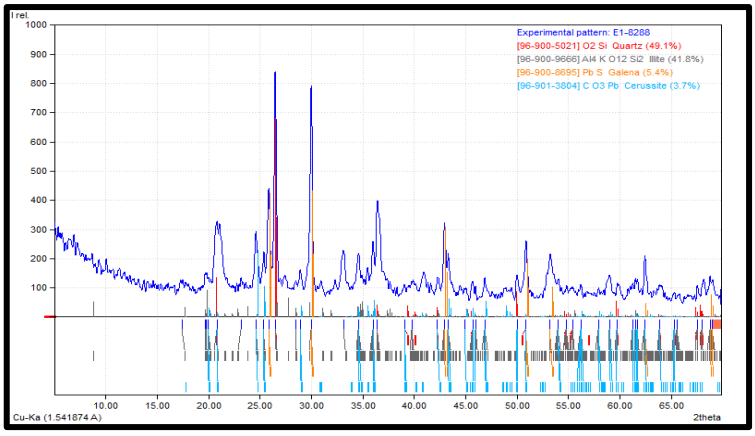


Figure 5. Diffractogram of Sample 1

3.2.2 Sample 2

The results of X-ray diffraction (XRD) analysis of Sample 2 show that the rock sample is dominated by anglesite ($PbSO_4$) with a relative abundance of 37.1%, followed by galena (PbS) at 29.6%. Other mineral phases identified in this sample include cerussite ($PbCO_3$) at 19.7% and quartz (SiO_2) at 13.6%. The diffractogram of Sample 2 is shown in the following figure (Figure 6).

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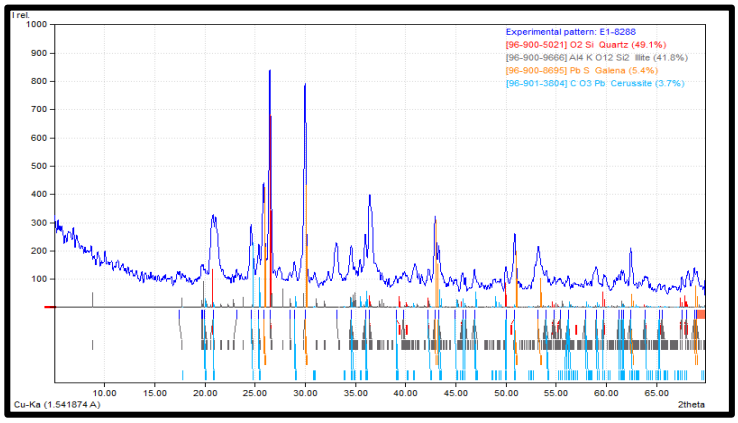


Figure 6. Diffractogram of Sample 2

3.2.3 Sample 3

The results of the XRD analysis of Sample 3 show that the rock sample is dominated by quartz (SiO_2), with a relative abundance of 89.5%. The ore mineral phases identified in this sample are chalcopyrite ($CuFeS_2$) at 8.9% and cerussite ($PbCO_3$) with 1.6%. The diffractogram of Sample 3 is shown in the following figure (Figure 7).

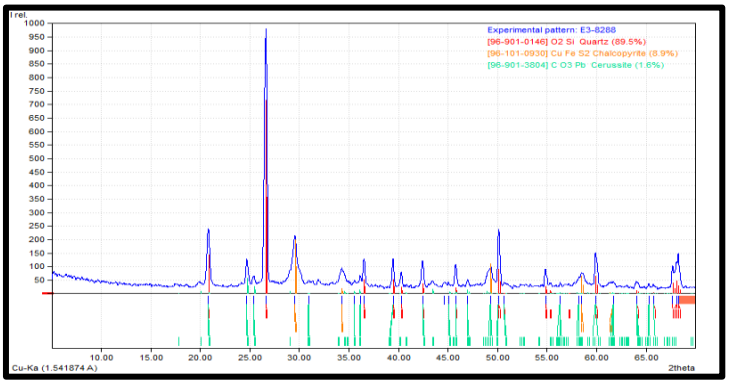


Figure 7. Diffractogram of Sample 3

A summary of the results of the mineragraphic and XRD analyses of the galena samples from the study area is presented in Table 1 below.

Table 1. Summary of the results of the mineragraphic and XRD analyses

No	Sample Code	Mineragraphic Analyses		XRD analyses	
		Ore Minerals	Associated Minerals	Ore Minerals	Associated Minerals
1	Sample 1	Galena (PbS) and Pyromorphite[$Pb_5(PO_4)_3Cl$]	Pyrite (FeS_2) and Quartz (SiO_2)	Galena (PbS) and Cerussite ($PbCO_3$)	Quartz (SiO_2) and Illite ($Al_4KO_{12}Si_2$)
2	Sample 2	Galena (PbS)	Pyrite (FeS_2), Malachite [$(Cu_2CO_3)(OH)_2$], Covellite (CuS), and Quartz (SiO_2)	Galena (PbS), Anglesite ($PbSO_4$), and Cerussite ($PbCO_3$),	Quartz (SiO_2)
3	Sample 3	-	Pyrite (FeS_2), Quartz (SiO_2,) Chalcopyrite ($CuFeS_2$)	Cerussite ($PbCO_3$)	Quartz (SiO_2) and Chalcopyrite ($CuFeS_2$)

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Based on the results of X-ray diffraction (XRD) analysis and mineralogical observations of rock samples from the study area, it can be determined that the ore minerals present in the three rock samples are galena (PbS), pyromorphite [$Pb_5(PO_4)_3Cl$], anglesite ($PbSO_4$), and cerussite ($PbCO_3$), with associated minerals consisting of quartz (SiO_2), illite ($Al_4KO_{12}Si_2$), pyrite (FeS_2), malachite [$(Cu_2CO_3)(OH)_2$], covellite (CuS), and chalcopyrite ($CuFeS_2$). The integrated interpretation of mineragraphic and XRD data reveals a clear distinction between primary hypogene minerals and secondary supergene products. Galena, pyrite, and chalcopyrite represent the primary sulfide assemblage formed under reducing hydrothermal conditions. In contrast, anglesite, cerussite, pyromorphite, malachite, and covellite are secondary minerals formed during later oxidation and supergene enrichment processes near the surface. The presence of these secondary minerals coating or replacing primary sulfides provides strong evidence of a multi-stage mineralization history involving both hypogene deposition and subsequent weathering-related modification.

3.3. Ore Texture

Based on the results of mineralogical analysis of samples 1, 2, and 3, the mineral textures of the ore found in the study area consist of disseminated, vein/veinlet, fracture-filling, replacement, coating, and cavity-filling textures.

3.3.1 Disseminated Texture

A disseminated texture was observed in Samples 1 and 3, characterized by the distribution of pyrite as euhedrasubhedral grains scattered throughout the quartz matrix without being concentrated along a specific vein. This distribution indicates that the mineralizing fluid was able to infiltrate the host rock relatively uniformly during the early stages of mineralization [11], [12].

3.3.2 Vein/Veinlet and Fracture-Filling Texture

These textures were observed in all three samples, as evidenced by quartz developing as veins (veins/veinlets) associated with sulfide minerals. In samples 1 and 2, galena fills fractures and intergranular spaces along the quartz vein pathways, indicating that the fracture structure served as the primary migration pathway for Pb-bearing fluids [12,13].

3.3.3 Replacement Texture

This texture was observed in all three samples. In sample 3, chalcopyrite replaced some of the pyrite at the crystal boundaries; at a later stage, chalcocite/covellite, as a supergene phase, replaced the chalcopyrite in the form of a thin rim. In samples 1 and sampel 2, part of the galena surface was replaced by secondary oxidation minerals (pyromorphite, anglesite, and cerussite). The presence of replacement textures in all samples indicates that mineralization occurred in several stages, with the primary sulfide minerals subsequently undergoing alteration due to fluid evolution toward more oxidative conditions [11-13].

3.3.4 Coating and Cavity-Filling Texture

These textures were observed in Sample 1 and Sample 2. In Sample 1, pyromorphite appears as a bluish-green coating and cavity filler on the surface of galena, while in Sample 2, malachite fills fractures with its characteristic green color [12]. Both of these textures are common characteristics of secondary minerals resulting from oxidation that form in near-surface zones (oxidation zones/gossans).

3.4. Paragenesis

Based on the results of mineralogical analysis of Samples 1, 2, and 3, the paragenesis of the ore minerals was determined based on the textural relationships among the minerals, particularly replacement, vein-filling, and coating/cavity-filling textures. Observations indicate that the sequence of mineral formation occurred in several stages, beginning with the deposition of siliceous gangue and primary Fe-Cu-Pb sulfides, followed by secondary minerals resulting from supergene enrichment and oxidation [14].

The early stage of mineralization (Stage I) is characterized by the formation of quartz (SiO_2) as the primary gangue mineral. This mineral develops as euhedral subhedral crystals, veins/veinlets, or a siliceous matrix that fills spaces in the host rock. Quartz reforms in Stage IV concurrently with the final stage of sulfide mineralization; thus, the quartz bar in the table appears twice, indicating that the silicification process is not continuous but rather occurs repeatedly at the beginning and toward the end of the hydrothermal system [15]. The next stage (Stages II-III) is marked by the formation of pyrite (FeS_2) as the first primary sulfide, followed by chalcopyrite ($CuFeS_2$), which partially replaces pyrite at the mineral contact boundary (replacement texture). This textural relationship indicates that pyrite is the earlier-forming sulfide phase compared to chalcopyrite, and both developed during the range from the early hypogene stage to the main hypogene stage [16], [17]. The subsequent stage (Stages IV-V) is marked by the

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formation of galena (PbS), which fills fractures and intergranular spaces and, in some areas, replaces previously formed sulfides. The presence of galena overlapping the end of the chalcopyrite stage indicates that Pb mineralization occurred after Cu-Fe mineralization, reflecting a shift in hydrothermal fluid composition toward the end of the hypogene phase [18], [19]. The final stage (Stages V-VI) is characterized by the formation of secondary minerals resulting from supergene enrichment and oxidation. Chalcosite/covellite (CuS) forms as a rim or through replacement of chalcopyrite during the supergene stage, while malachite, anglesite, cerussite, and pyromorphite form during the final oxidation stage as a coating or through replacement of galena and chalcopyrite [20], [21]. The presence of these minerals at the end of the diagram indicates that they represent the youngest mineralization phases, formed after the primary hydrothermal system ceased activity and the rock came into contact with a near-surface oxidative environment. A summary of the stages of paragenesis is presented in Table 2 below.

Table 2. Summary of the stages of paragenesis

Mineral	Stage I	Stage II	Stage III	Stage IV	Stage V	Stage VI
Quartz (SiO_2)	Vein-Filling			Vein-Filling		
Pyrite (FeS_2)		Replacement	Replacement			
Chalcopyrite ($CuFeS_2$)			Replacement	Replacement		
Galena (PbS)				Cavity-Filling	Cavity-Filling	
Chalcocite/ Covellite (CuS)					Replacement	Replacement
Malachite $[(Cu_2CO_3)(OH)_2]$						Replacement
Anglesite, Cerussite, Pyromorphite						Replacement

4. Conclusion

The conclusions of this study are that the types of ore minerals in the deposits were identified based on the results of X-ray diffraction (XRD) and mineralogical analysis and consist of galena (PbS), pyromorphite $[Pb_5(PO_4)_3Cl]$, cerussite ($PbCO_3$), and anglesite ($PbSO_4$). The associated minerals are quartz (SiO_2), illite ($Al_4KO_{12}Si_2$), pyrite (FeS_2), malachite $[(Cu_2CO_3)(OH)_2]$, covellite (CuS), and chalcopyrite ($CuFeS_2$). The mineral textures observed in samples 1, 2, and 3 include: disseminated, vein/veinlet, fracture-filling, replacement, coating, and cavity-filling textures. The paragenetic stages begin with the early stage, characterized by the formation of quartz as the primary gangue mineral, followed by pyrite and chalcopyrite as primary sulfides during the hypogene stage. The subsequent stage is marked by the formation of galena as a primary sulfide that fills fractures and intergranular spaces, as well as partially replacing the previous sulfides. The final stage is marked by the formation of secondary minerals resulting from supergene enrichment (calcosite/covellite) and oxidation (malachite, anglesite, cerussite, and pyromorphite), which partially replace galena and chalcopyrite through replacement textures and coat the surfaces of the primary minerals (coating).

Author contributions: Muhamad Hardin Wakila: Conceptualization, methodology, supervision, project administration, and writing review and editing. Alfian Nawir: Data curation, investigation, formal analysis, visualization, and writing original draft preparation. Harwan and Mubdiana Arifin: Investigation and validation. Yushar Khatib Warta: Validation and writing review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare that there are no conflicts of interest.

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