CHARACTERIZATION OF POLYMETALLIC-GOLD DEPOSIT OF EASTERN MANSON'S LODE, ULU SOKOR, KELANTAN

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Abstract. Polymetallic gold in Manson's Lode pit and Ulu Sokor Gold Mine in Kelantan are hosts to significant gold (Au) and base metal deposits. The deposit is hosted in Permo-Triassic meta-sedimentary and subordinate volcaniclastic rocks. Field observation and geochemistry sampling of ore zones have been carried out in Manson's Lode Eastern pit to determine the type of sulphide minerals and ore composition in the ore body. The Eastern Pit is the hard rock extension below the main ore body, and this condition provides good samples for geochemistry sampling. Selected samples were collected and prepared for lab analysis using scanning electron microscope (SEM) and inductively coupled plasma mass spectrometry (ICP-MS) to confirm field observations of ore mineral composition. The polymetallic ores were subdivided into three main zones of mineral association. The upper zone is sheared carbonaceous host rock with pyrite-galena veins localized along the shear zone. The middle zone is rich with sphalerite-galena-pyrite within quartz carbonate veins and hosted within meta-siltstone. The lowest zone is dominated by pyrite with localised sphalerite. ICP-MS analyses of six ore samples indicate the average content of elements is 103,333 ppm iron (Fe), 4,031.7 ppm lead (Pb), 5,000.0 ppm zinc (Zn), 1,937.3 copper (Cu), and 0.6 ppm gold (Au), which represent the sulphide minerals pyrite, galena, sphalerite, chalcopyrite, and gold, respectively. However, Cu and gold are erratic across the ore zone and much higher grade in the upper zone. The gangue minerals include quartz and carbonates consisting of calcite, siderite, and dolomite. The Pearson correlation coefficient matrix shows the relationship between the elements in this deposit. The correlation determined for 20 elements shows that Au is well correlated with Cu, Bi, Sb, Sn, Te, Co, and Ni.

Keywords: Geochemistry, polymetallic, sulphide mineral, gold

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Introduction

The Central belt of Peninsular Malaysia has been known to host significant gold deposits, especially of the orogenic type [1-3]. Commonly known gold deposits such as those in Malaysia are associated with the veins and sulphide minerals, including pyrite, arsenopyrite, sphalerite, galena, and minor base metals [1,4]. However, significant polymetallic sulphide associated with gold mineralization can be found in the eastern part of the Ulu Sokor deposit. Pyrite is the common sulphide mineral present in all pits in Ulu Sokor, but one pit, which is referred to as the Manson's lode, has abundant base metals and sulphide minerals. Polymetallic-gold mining is one of the important sectors for the mineral industry, which was being considered as the main source for the growth and development of Malaysia. It would provide a great potential to the economy due to its high price and popular use; for example, gold is used for jewelry, the electronics industry, dental alloys, medals, and coinage. Ulu Sokor deposit, Kelantan, and the Tasik Chini deposit in Pahang were previously classified as volcanogenic massive sulphide [5-6]. In Peninsular Malaysia, 27 gold prospects and primary deposits, including Penjom, Selinsing, and Raub [5-7].

The Ulu Sokor gold deposit is one of the largest gold deposits in the Central Belt of Peninsular Malaysia. This region also hosts the primary gold mineralisation identified as mesothermal lode styles, orogenic gold and sediment hosted gold deposits. These deposit classifications are based on the tectonic and geological setting of the Central Gold Belt [3,5,8]. This belt is located in between the Western and Eastern Belts of Malaysia, and this subdivision is the result of subduction and subsequent faulting [9,10]. The local host rocks comprise felsic to intermediate volcanic rocks that occur within a more extensive area of marine clastic and argillaceous sedimentary rocks [6]. The Permian-Triassic meta-sedimentary mainly consists of phyllite, crystal tuff, slate, shale, limestone, interbedded sandstone, siltstone, and with lesser amounts of volcaniclastics [4-5].

Gold mineralisation is associated with hydrothermal quartz veins, disseminated and massive sulphide. The main factors contributing to the succession of gold mineralization are hydrothermal sources and depositional structure. The Ulu Sokor deposit consists of three major orebodies related by north-south (NS) to north-east (NE) striking fractures within fault zones in Permian-Triassic meta-sedimentary and volcanic rocks of the East Malaya Block. Based on the previous study such as fluid inclusion, sulfur isotope, oxygen, and hydrogen isotope indicate the gold mineralization is consistent with the classification of the orogenic gold deposit in Ulu Sokor, including Manson's Lode Pit [11]. There is a possibility of multiple mineralization episodes and sources in Manson's Lode that require further study to infer the main source of mineralization.

This study focuses on the Manson's Lode, one of four identified gold deposits in the Ulu Sokor gold field project, along with New Discovery, New Found, Sg. Ketubong, and Rixen. This study includes the microscopic observation of the rock type in thin sections. Correlations between the elements were analyzed based on the Pearson correlation coefficients to measure the linear relationship between elements. The objectives of this study are to determine the mineralogy and geochemistry of a polymetallic-gold deposit, especially the minerals present in the eastern part of Manson's Lode, Ulu Sokor, that can be used to access the hard rock potential of this lower zone of the overall Manson's Lode ore body.

Materials and Methods

Field observation has been carried out on the Ulu Sokor deposit to collect geological data and understand the distribution of polymetallic gold deposits at the Eastern Manson's Lode pit. This study focuses on the geochemistry sampling at the slope face and pit floor to represent the top-to-bottom vertical sequence that crosses the vertical section of the orebody. The grab samples were collected at 14 locations and labelled MLA to MLN across the slope. Three samples were prepared for the thin section study (samples labelled as MLE, MLG, and MLL); selected samples were prepared for the polished section and analyzed with Scanning Electron Microscopy-Energy Dispersive X-ray Spectrometer (SEM-EDX), model Zeiss-Supra 35VP for area mapping and spot analysis. Six samples were prepared for multi-element analysis by inductively coupled plasma mass spectrometry ICP-MS at Activation Laboratories lab (Canada).

For polished sections, the samples were cut using a cutter blade machine and trim machine to produce a smooth cut for thin and polished section preparation. The epoxy resin and hardener were mixed homogeneously and poured into a mounting mold containing a sample. The mounted samples were ground, followed by an oil polishing procedure for an hour until a smooth and clean surface was acquired. Samples were impregnated for thin section preparation to make sure the samples would not easily break. The rock section was stuck to the glass slide with a strong adhesive. The excess part of the section is cut off using a Petro Thin Machine. Finally, the samples were polished by hand with 600-grit silicon carbide powder abrasive paper. The samples were observed using reflected and transmitted light microscopy for polished and thin sections. SEM images were obtained using both secondary (SE) and back-scattered (BSE) electrons, equipped with an EDX for element composition.

The rock samples were crushed and then dried at 110 °C for 12 hours to remove all moisture or excess water. The crushed ore from the jaw crusher was collected and fed into the cone crusher. Secondary crushing was done because the size reduction from primary crushing was insufficient to yield a suitable size. The samples were later grinded using a 240-volt agate with a vibrating ring mill for 3 minutes to achieve a suitable size. The samples were then weighed to obtain 25 g for each sample. Approximately 3-5 g of samples were used for X-ray diffractometer (XRD) analysis. Fourteen samples were analyzed using an advanced powder XRD analysis (Bruker AXS, D8 Advance, Karlsruhe, Germany) to quantitatively determine the mineral present and percentage. XRD analysis works by emitting incident X-rays to a mineral in the powder samples, and the intensities and scattering angles of the diffracted X-rays from the mineral's crystal structures are measured. The Xpert High Score Plus and the Pan Analytical ICDD (Inorganic Crystal Database) for mineral identification were used to analyze the XRD results. The pulverized samples were also used for elementary analysis. Sample decomposition for major and trace element geochemistry analysis by aqua regia ICP-MS analysis was performed for the multi-element analytical method by having detection limits across the whole mass range, which are superior to most conventional techniques.

Results and Discussion

Field Observation

Based on the field observations, the polymetallic ore at Manson's Lode is subdivided into three main types of mineral associations (Figure 1). The upper zone is sheared carbonaceous host rock with a thin pyrite-galena vein localized along the shear zone. The middle zone hosted within meta-siltstone is rich with coarse galena-sphalerite and pyrite within a quartz carbonate vein. The lowest zone is dominated by pyrite with localized sphalerite and galena of 2 to 4 cm size. The total thickness of all sequences is about 20 m. These three sequences of ore (gold and base metal) are sub perpendicular to the strike of the slope wall. Sedimentary bedding is oriented approximately 35º and gently dips to the east. The shear is oriented about 45º at a low angle, running sub-perpendicular to the carbonaceous shale. The presence of rhyolite porphyry associated with sedimentary and metamorphic rocks such as phyllite observed in other pits, such as at New-Found, may indicate volcanic activity before or during the formation of ore deposit. The fresh samples collected in this study provide the original mineral concentration without modification by the weathering process. Previously, higher-grade deposits (near the surface and in the west zone extension) had been mined prior to this study that were made up of the highly oxidized zone with limestone lenses. Supergene enrichment in the oxide zone contributed to the surface higher-grade ore and significant argentiferous-auriferous massive pyritic lead-zinc sulphide bodies in Ulu Sokor were reported by [9,12]. These ore bodies show supergene gold enrichment, with the oxidised zones displaying a higher gold tenor than the primary sulphide.

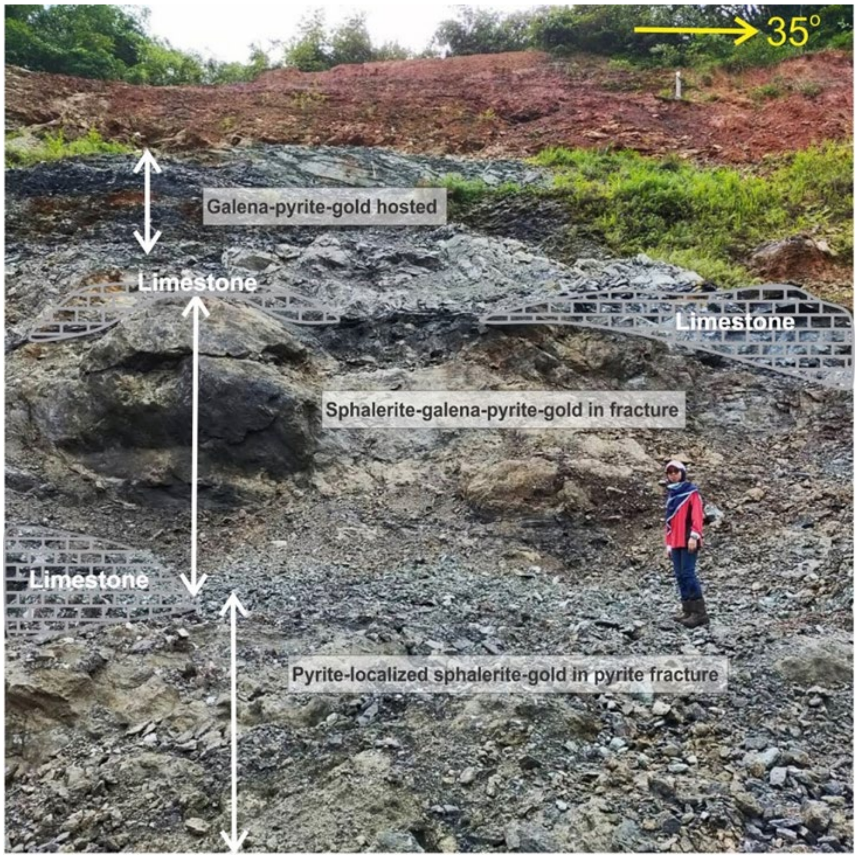

Figure 1: Close-up view of the outcrop and three horizons (upper, middle, and lower) of sulphide minerals and gold mineralization on the eastern part of the Manson's Lode

Microscopic Study of Thin Section

Samples MLE, MLG, and MLL have been observed for thin section analysis (Figure 2). Sample MLE is composed principally of calcium carbonate (calcite-$CaCO_3$) with perfect rhombohedral cleavage and colorless pleochroism in thin section. MLG and MLL represent calcium magnesium carbonate (dolomite-$CaMg(CO_3)_2$), quartz (SiO_2) and an opaque pyrite (FeS_2). Dolomite minerals are colorless to grey with a variable high-to-low relief on stage rotation. Quartz appears colorless and has no pleochroism. The shape is a typical anhedral grain of silty to sandy size. All samples are interpreted as calcareous siltstone and sandstone.

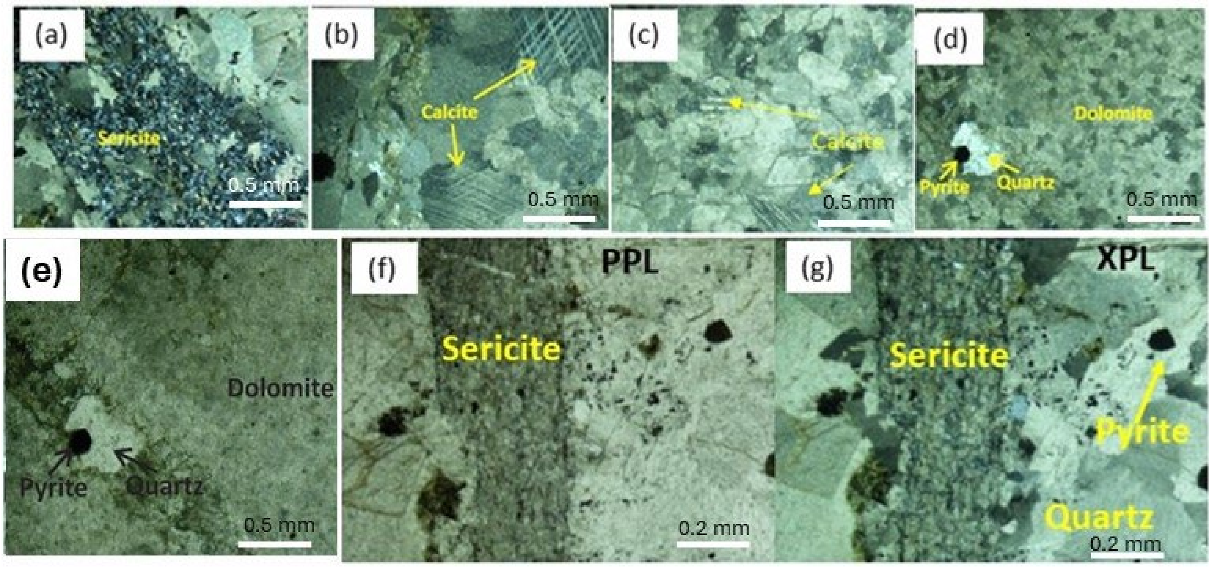

Figure 2: Photomicrograph of minerals in cross-polarized light; (a) Sericite crystallizes in quartz grain (sample MLE). (b) Calcite in visible polysynthetic twinning and intergrown between feldspar and quartz (sample MLE). (c) Sample MLG intergrown with dolomite and calcite grains. (d) Sample MLL made up of silty-sized dolomite, quartz, and pyrite (e) MLL - Dolomite with quartz and locally pyrite (f) MLE - Plane-polarized Light (PPL) Sericite and (g) MLE - Crossed Polarized Light image (XPL), Sericite is associated with pyrite and quartz.

Microscopic Study of Polished Section

Based on field observation and petrography analysis under the polarizing microscope, the most abundant and widespread minerals present in all samples are sulphide mineral assemblages such as pyrite, galena, sphalerite, and chalcopyrite. Figure 3 shows the occurrences of the sulphide mineral in the samples and its relationship with other minerals. Pyrite (FeS_2) occurs as subhedral to euhedral grains ranging in size from 0.03 to 0.5 mm. Some of the pyrite was observed as corroded, pitted, and fractured, and hosted in quartz as well as disseminated in the wall rock. Galena (PbS) is bluish-white and locally has triangular cleavage pits. Galena occurs as fine to coarse aggregates infilling interstices in between grain boundaries and fractures in pyrite and sphalerite.

Sphalerite is a zinc sulfide mineral (ZnS), appearing dark gray in color and occurring as fine to coarse grains, subhedral to anhedral in shape. Forming as massive aggregate sphalerite that fills in the fractures. Chalcopyrite ($CuFeS_2$) is the least abundant mineral found at the site compared to the other sulphide minerals. Chalcopyrite appears as a yellowish green material of irregular form and size with subhedral and anhedral crystals. It can be found together with pyrite, galena, and sphalerite as fracture filling or inclusions within early sulphide minerals. Lastly, pyrrhotite (FeS) is composed of iron sulfide with a brassy yellow to light-red color. Pyrrhotite also commonly occurs with pyrite in geological environments that underwent low-grade metamorphic history.

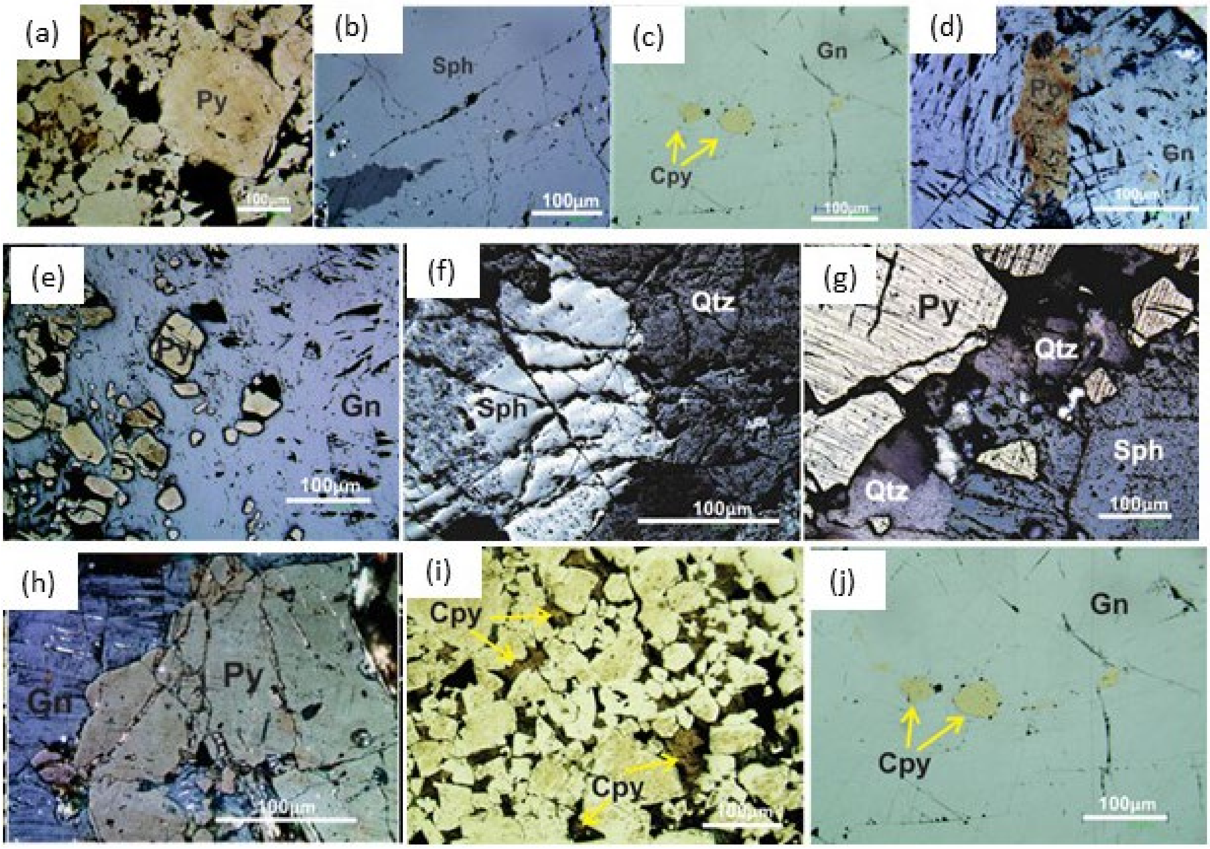

Figure 3: Photomicrograph of minerals in reflected light: (a) Subhedral-anhedral pyrite. (py) grains (sample MLA). (b) Sphalerite (Sph) appears dark grey in color and occurs as fine to coarse grains (sample MLB) (c). Chalcopyrite (Cpy) as yellowish mineral of irregular form and size (sample MLA), and galena (Gn). (d) Pyrrhotite (Po) brass yellow to copper-red colour (sample MLA). (e) Galena dominantly occurs intergrown with pyrite as inclusions. Luster fractured sphalerite associated with quartz grains in MLJ. (f) Luster-fractured sphalerite associated with quartz grains in MLJ. (g) Pyrite in sample MLH is subhedral in places with irregular-grain sphalerite and quartz. (h) MLA sample with galena associated with pyrite. (i) Chalcopyrite intergrowth with subhedral or euhedral pyrite grains appears in small and yellow tint and (j) Chalcopyrite as small rounded to subangular grains appears as a light yellowish inclusion in galena texture.

SEM-EDX Mineralogy Analysis

The elemental composition of the Manson's Lode Eastern ore is based on the analysis of eight samples by SEM-EDX that show substantial amounts of geochemical contents (Figure 4). Area mapping can be performed first, with later selection of the elementary spot analysis confirming the composition. In this study, the elements encountered are the polymetallic sulphide minerals Fe-Zn-Pb-As-Au-Cu.

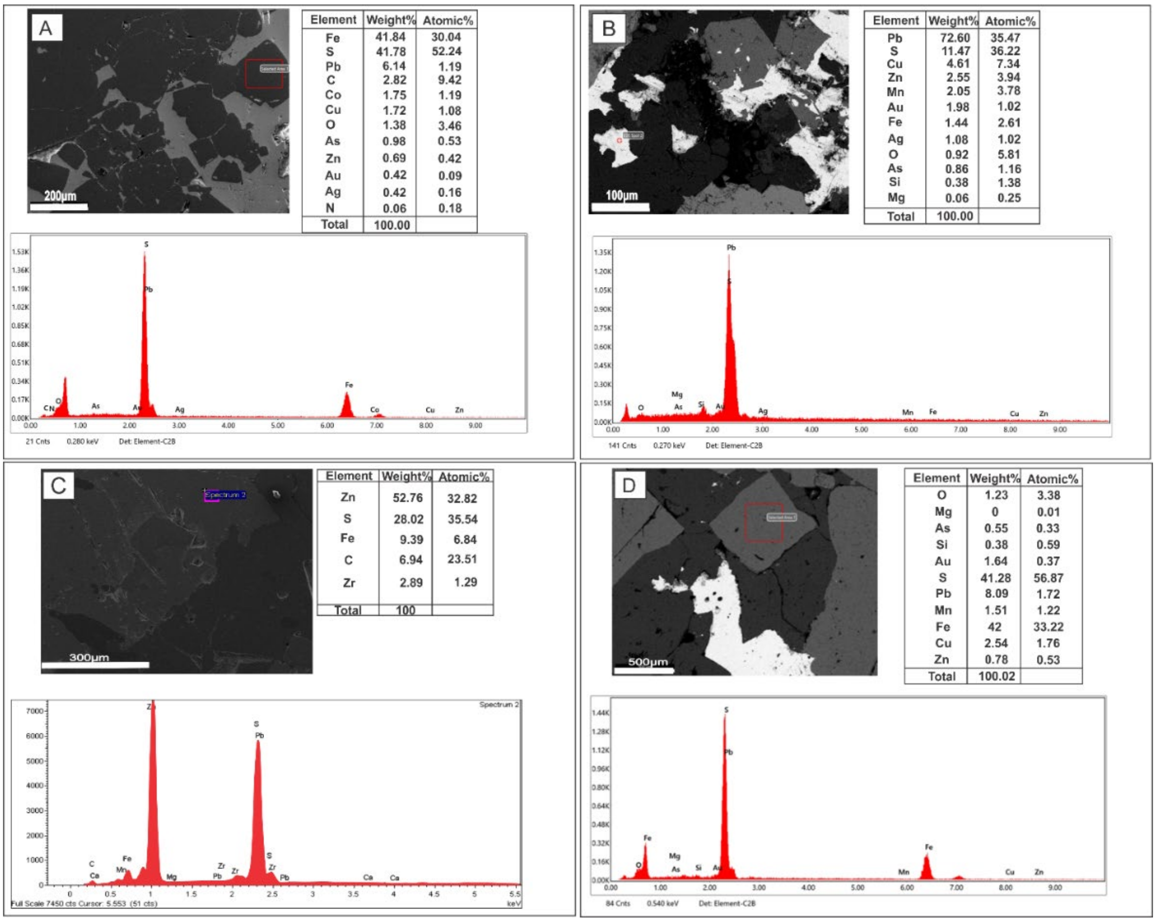

Figure 4: SEM-BSE images along with EDS plots; represent highly base metal minerals (A) MLA-pyrite; highly concentration of Fe (41.84%) and S (41.78%), (B) MLD-galena; with high Pb (72.60%) and S (11.47%). (C) MLH-sphalerite with high Zn (52.76%) and S (28.02%) respectively and (D) Selective area analysis, MLJ-pyrite with Fe 42% and S (41.28%).

The sulphide minerals, especially galena and pyrite, show a higher volume percentage in the ore samples (upper horizon) and galena-sphalerite (middle horizon). SEM-BSE images along with EDX charts (Figure 5) indicate that samples from the MLA (upper horizon) have Fe (41.84%) and S (41.78%) on the pyrite grain, MLD (middle horizon) has Pb (72.60%) and S (11.47%) and MLI on the lower horizon is highly content with S (39.59%) and Fe (31.31%), dominantly massive pyrite-rich minerals. MLA, MLD, and MLH have a trace of gold ranging from 0.98 ppm to 1.98 ppm that may occur as an ultra-fine inclusion within pyrite and galena. Figure 5 shows the area mapping of the MLD sample and the galena-pyrite mineral association. Area mapping for MLD indicates the dominant elements that represent PbS, SiO_2 and FeS_2.

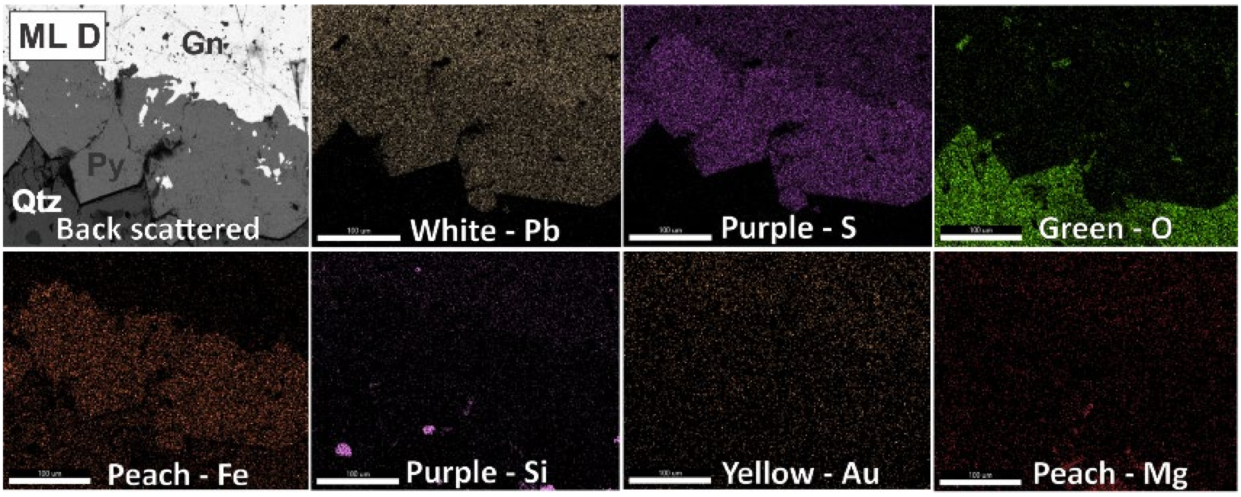

Figure 5: SEM-EDX area mapping of the Manson's Lode deposit composition for MLD sample dominated with galena (Ga), pyrite (Py) and quartz (Qtz) (scale bar= 500 µm).

XRD Analysis

The mineralogy of the polymetallic components has been determined using XRD. These analyses were conducted for various samples representing different geological or mineralization features. Based on the XRD analysis shown in Table 1, the main mineralogy of the ore from Manson's Lode is pyrite, galena, and sphalerite. In addition, chalcopyrite and arsenopyrite were also detected in the samples. In the oxide zone, minerals detected are hematite (MLC-old stockpile, MLF-oxidized zone), magnetite (MLC, MLF), and carbonate minerals such as dolomite (MLD, MLG) and siderite (MLD, MLE, MLJ) can be found in three samples in Horizon 2 and Horizon 3. Additional samples (R1, J1, H1 and NF1) show dominant pyrite and quartz in Horizon 3. Based on XRD analysis, three horizons of sulphide mineral association with gold can be determined, such as Horizon 1 (pyrite- galena), Horizon 2 (sphalerite-galena-pyrite), and Horizon 3 (Pyrite - localized Sphalerite).

The mineral phases that represent the peaks have been shown in Table 1. On the other hand, Rietveld analysis has defined the phases of the sample. MLA presented pyrite with 1.0% matched with ICDD card no. 98-000-5932 data, galena with 98.9% (ICDD card no. 98-002-1787), and sphalerite with 0.1% (ICDD card no. 98-009-8117). Further, pyrite was recognized with 12.7% (ICDD card no. 98-000-5730) and sphalerite with 87.3% (ICDD card no. 98-006-1517) phases in sample MLH. Meanwhile, MLM matches the reference data with pyrite (99.4%) (98-004-9029), sphalerite (0.05%) (98-006-1510), and arsenopyrite (0.1%; 98-007-8990). The phases reported were referred to the ICDD as a standard reference.

Table 1: Phase identification and quantification by XRD analysis (value of minerals in %)

Samples	Pyrite	Galena	Sphalerite	Hematite	Magnetite	Quartz	Dolomite	Siderite	Chalcopyrite	Arsenopyrite	Others
MLA	1.0	98.9	0.1	-	-	-	-	-	-	-	-
MLB	11.8	13.1	75.1	-	-	-	-	-	-	-	-
MLC	-	-	18.3	76.3	5.4	-	-	-	-	-	-
MLD	-	-	1.0	-	-	3.4	63.6	32.0	-	-	-
MLE	28.9	-	2.7	-	-	3.8	-	64.6	-	-	-
MLF	-	-	-	66.7	1.9	-	-	-	-	-	31.4
MLG	66.6	-	-	-	-	-	33.4	-	-	-	-
MLH	12.7	-	87.3	-	-	-	-	-	-	-	-
MLI	83.0	-	0.6	-	-	-	-	-	16.4	-	-
MLJ	0.3	3.1	4.5	-	-	-	-	92.1	-	-	-
R1	13.6	-	-	-	-	86.4	-	-	-	-	-
H1	40.5	-	23	-	-	-	-	-	21	-	15.5
J1	80.1	-	19.9	-	-	-	-	-	-	0.1	-
NF1	39.3	-	-	-	-	54.3	-	-	-	0	6.4

Trace element geochemistry by ICP-MS

Geochemical analyses of the grab samples of 63 elements, such as sulfur (S), iron (Fe), gold (Au), lead (Pb), arsenic (As), zinc (Zn) are tabulated in Table 2. The most abundant elements are Fe and S, ranging from 113,000 ppm to 231,000 ppm and 10,000 ppm to 180,000 ppm, respectively, and contributed largely by pyrite and other sulphide minerals. Au is present within the ore horizon of the polymetallic-gold mineralization up to 2.7 ppm. The other trace elements are Pb (890 - >5000 ppm), As (87.7 - >10,000 ppm), Zn (585- >5,000 ppm), and Cu (72.5-8230 ppm). These results support the polymetallic ore deposit associated with Au in Manson's Lode within the hard rock sequence. Fe comes mainly from pyrite in the form of massive coarse grain and is disseminated in the host rock, while arsenopyrite is mainly disseminated. Locally, Pb and Zn coexist in the form of galena and sphalerite. Mn usually comes from the secondary minerals that form due to the weathering process.

Table 2: Trace element geochemistry (in ppm) from Manson's Lode deposit by ICP-MS analysis. Maximum limit of the data in ppm are Ag (100), Pb (5,000), As (10,000), Zn (5,000), Mn (10,000)

Element	ML A	ML B	ML D	ML H	ML I	ML J	*Mean*	*Median*	*Std. Dev*
S	140,000	120,000	10,000	100,000	180,000	70,000	103,333	110,000	58,878
Fe	113,000	204,000	179,000	175,000	197,000	231,000	183,167	188,000	39,802
Au	2.7	0.0	0.3	0.6	0.0	0.2	0.6	0.2	1.0
Hg	0.1	1.1	0.2	0.8	0.1	0.7	0.5	0.5	0.4
Ag	100.0	100.0	9.8	42.7	38.3	100.0	65.1	71.4	39.8
Pb	5,000.0	5,000.0	3,300.0	5,000.0	890.0	5,000.0	4,031.7	5,000.0	1,682.6
As	788.0	10,000.0	87.7	10,000.0	691.0	197.0	3,627.3	739.5	4,943.7
Zn	585.0	5,000.0	5,000.0	5,000.0	781.0	5,000.0	3,561.0	5,000.0	2,230.2
Mn	404.0	10,000.0	10,000.0	6,950.0	6,280.0	10,000.0	7,272.3	8,475.0	3,757.2
Cu	8,230.0	882.0	89.1	1,090.0	72.5	1,260.0	1,937.3	986.0	3,123.5
Bi	2,000.0	25.4	2.0	12.1	99.3	18.2	359.5	21.8	804.4
Mo	1.8	1.1	1.3	2.9	2.1	2.6	2.0	2.0	0.7
Cd	22.8	861.0	61.4	1,650.0	3.4	332.0	488.4	196.7	655.3
Sb	191.0	98.9	3.9	81.3	5.9	84.2	77.5	82.8	69.2
Sn	149.0	16.0	5.0	12.3	7.6	11.1	33.5	11.7	56.7
Te	15.4	0.2	0.2	0.3	9.2	0.1	4.2	0.3	6.6
Ba	0.5	1.9	5.1	2.6	2.8	2.4	2.6	2.5	1.5
Co	4.3	1.3	0.3	0.6	0.4	0.4	1.2	0.5	1.6
Se	0.9	4.1	0.7	12.5	0.3	1.6	3.4	1.3	4.7
Ni	6.3	3	5	3.7	2.9	3	4.0	3.4	1.4

The Manson's Lode polymetallic sulfides are hosted by sedimentary sequences that have been partly metamorphosed to phyllite with subordinate limestone, calcareous siltstone, and meta-sandstone layers sub-parallel to the stratigraphy. The host rock was subjected to regional low-grade metamorphism, which may imply the circulation of metamorphic and/or intrusive source fluids related to the Permo-Triassic orogenic event. Base metal sulphide minerals are apparently less abundant in the limestone unit compared to phyllite and calcareous siltstone. Due to the lack of a volcanoclastic unit or volcanic rock within Manson's Lode orebody therefore, the Manson's Lode is not suitable to be classed as an exhalative deposit as previously reported [12-15] so there is no direct evidence of a fluid source that is derived from a volcanogenic origin. In comparison to the Tasik Chini volcanic hosted massive sulphide deposit, which has the characteristics of a volcanogenic origin [6] with pyrite, chalcopyrite, and less sphalerite and rarely galena. The Manson's Lode East has a different combination of pyrite, galena, sphalerite, and arsenopyrite as a dominant sulphide mineral and a lesser amount of chalcopyrite.

Conclusions

The geochemistry of the eastern Manson's Lode hard rock deposit supports the presence of base metal and massive sulphide within the ore body and invisible ultra-fine Au in pyrite or in the quartz carbonate vein. Primary sulphide minerals, mainly pyrite, galena, and sphalerite, form the main part of the body. Lesser amounts of pyrrhotite, chalcopyrite, dolomite, and calcite were presented. Among the important elements such as Au, Pb, Zn, Cu, As, Mn, Ag, and Bi in Manson's Lode East have almost similar mineral assemblages to orogenic gold in Malaysia.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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