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Mineralogy and Geochemistry of Gold Mineralization at Southern Part of Ulu Sokor Gold Deposit, Kelantan, Malaysia

(Mineralogi dan Geokimia Pemineralan Emas di Bahagian Selatan Longgokan Emas Ulu Sokor, Kelantan, Malaysia)

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ABSTRACT

The Ulu Sokor gold deposit is classified as orogenic type deposit with evidence from previous studies on the structural, mineralogical, alteration, fluid inclusion, and stable isotope data. This study focuses on the mineralogy and geochemical analysis of representative ore rock samples from southern part of Ulu Sokor gold deposits. The project area is situated at the North of Kelantan state which lies on the Central Belt of Peninsular Malaysia. The main objective of this research is to determine the gold mineralization enrichment pattern relative to other trace elements based on the new data of mineralogy and geochemical analysis. Gold mineralization is primarily hosted in structurally controlled quartz vein which occurs in various degrees of ductile-brittle environment. Based on the field relationships, ore microscopy and geochemical data analysis, there are two main gold mineralization type in the southern part of Ulu Sokor gold deposit, namely (1) Gold associated and as inclusions in bismuthinite based on the mineralogy study, and (2) Refractory gold occurs as lattice bound in pyrite based on the Au/As molar ratio. In terms of mineral exploration and gold prospecting, the significant enrichment in this study area is Bi. However, some other metals can also be considered as a significant value in this area such as Pb, As, Cu and Zn. From the bulk ore chemistry, the geometric mean values of Au and Bi are 1.9 ppm Au (n=23) and 96 ppm Bi (n=22), respectively. The knowledge base for bismuth minerals in Malaysia would provide a significant targeting clue for the gold mineralization.

Keywords: Bismuthinite; geochemistry; gold; mineralogy; Ulu Sokor

ABSTRAK

Longgokan emas di Ulu Sokor dikelaskan sebagai longgokan jenis orogeni berdasarkan data daripada kajian struktur geologi, mineralogi, pengubahan mineral, inklusi bendalir dan isotop stabil. Kajian ini memberi tumpuan pada analisis mineralogi dan geokimia bagi sampel batuan di bahagian selatan longgokan emas Ulu Sokor. Kawasan kajian terletak di bahagian utara negeri Kelantan yang termasuk dalam Jalur Tengah, Semenanjung Malaysia. Kajian utama penyelidikan ini adalah untuk menentukan corak pengayaan pemineralan emas yang berhubung kait dengan unsur surih yang lain berdasarkan data mineralogi dan analisis geokimia baru. Pemineralan emas ini secara majoritinya terbentuk dalam hos telerang kuarza yang dikawal oleh persekitaran struktur mulur-rapuh. Berdasarkan bukti di lapangan, mikroskopik bijih dan data analisis geokimia, terdapat dua jenis pemineralan emas yang utama di kawasan selatan longgokan emas Ulu Sokor, (1) Pemineralan emas sebagai inklusi atau berasosiasi dengan mineral bismutinit dan (2) Emas refraktori berlaku sebagai kekisi terikat dalam pirit berdasarkan nisbah molar Au/As. Mengikut eksplorasi mineral dan prospek emas di kawasan kajian, pengayaan unsur Bi adalah lebih penting. Walau bagaimanapun, terdapat juga unsur logam lain yang menunjukkan nilai yang penting seperti Pb, As, Cu dan Zn. Data daripada pukal kimia bagi bijih, nilai purata geometri unsur Au dan Bi adalah masing-masing bernilai 1.9 ppm Au (n=23) dan 96 ppm Bi (n=22). Pengetahuan untuk mineral bismut di Malaysia akan memberikan petunjuk sasaran penting untuk pemineralan emas.

Kata kunci: Bismutinit; emas; geokimia; mineralogi; Ulu Sokor

Introduction

In the early 15th century, Southeast Asia Peninsular was known as Aurea Chersonesus or Golden Peninsula. This first world map was led by Claudius Ptolemy in the early of the 2nd century. However, it was revised by Muhammad Ibn Musa al-Khwarizmi in the early 9th century in terms of city coordinates and other geographical features (Ayyubi 2006). Peninsular Malaysia was established as an important gold producer in the past before the discovery of enormous goldfield such as in the Witwatersrand Basin, Johannesburg, South Africa. The long history of minor scale gold mining activities was done at the Central Belt of Peninsular Malaysia such as in Kelantan and Pahang states.

The deposition of gold at Central Belt of Peninsular Malaysia was controlled by the regional Bentong-Raub suture zone which formed during amalgamation of the Sibumasu Block and the East Malaya Block in Late Triassic to Early Jurassic (Metcalfe 2000). The development of gold mineralization at Central Belt of Peninsular Malaysia is significant to the hydrothermal fluid activity, located in Ulu Sokor and Pulai (Kelantan) and Buffalo Reef, Selinsing, Penjom, Kechau Tui and Tersang (Pahang) (Ariffin & Hewson 2007; Goh et al. 2006).

The gold deposits at both Ulu Sokor dan Selinsing are currently active with fine gold production. From 2015 to 2020, the gold production reported in Ulu Sokor is 146,083 ounces (Snowden Optiro 2019), while the gold production at Selinsing is reported 321,694 ounces from 2010 to 2020 (Monument Mining Limited 2019). Until 31st December 2019, the total measured, indicated and inferred gold mineral resources at Ulu Sokor deposit is 16,320 k tonnes at 1.7 g/t gold (Snowden Optiro 2019). Meanwhile in 2019, an updated NI 43-101 project report with title 'Selinsing Gold Sulphide Project' ('the 2019 Feasibility Study') produced by Snowden Mining Industry Consultants Pty Ltd fully replaced the existing gold inventory with gold resources of 880 k oz and reserves of 267 k oz at 1.45 g/t to extend the mine life by a further six years with upside potential (Monument Mining Limited 2019).

This study focuses on the mineralogy and geochemical analysis of representative ore rock samples from southern part of Ulu Sokor gold deposits which located at the Central Belt of Peninsular Malaysia. According to Goldfarb et al. (2001), Groves et al. (2003, 1988), and Li et al. (2015), the most important mechanism involving gold deposition in this study area is fluid immiscibility and consistently to be classified as an orogenic gold deposit.

The main objective of this research was to determine the gold mineralization enrichment pattern in relative to other trace elements based on the new data of mineralogy and geochemical analysis.

Tectonic Setting of Peninsular Malaysia

Peninsular Malaysia is a part of Southeast Asia in the continental crust of Sundaland (Metcalfe 2013a). In general, Peninsular Malaysia comprises of two tectonic blocks which are Sibumasu Block on western part and East Malaya Block on the eastern part. Sibumasu Block was derived from the northwest of Australian Gondwana by late Early Permian, while East Malaya Block was derived from Gondwana margin by Early Devonian (Metcalfe 2013a). The two block were assembled by Late Triassic along the major suture line called Bentong-Raub suture zone (Metcalfe 2013b).

Peninsular Malaysia is locally subdivided into Western, Central and Eastern Belts based on stratigraphy, structural, igneous geochemistry, and geophysical interpretation done by previous studies (Metcalfe 2013a, 2013b, 2000; Yeap 1993). Western Belt lies within Sibumasu Block, while Central and Eastern Belts as East Malaya Block. However, in term of economic mineral mineralization pattern, Peninsular Malaysia can be divided into three distinct belts which are Western Tin Belt, Central Gold Belt, and Eastern Tin Belt (Yeap 1993) (Figure 1). The formation of Bentong-Raub suture zone is related with the subduction of the Palaeo-Tethys Ocean beneath the East Malaya Block and it was believed that it was initiated during Carboniferous period (Figure 2). However, it was completely closed by Late Triassic to Early Jurassic period (Metcalfe 2000).

Local Geology of Central Belt of Peninsular Malaysia

In general, Central Belt is deposited in a forearc portion of the palaeo-arc basin (Gobbett & Hutchison 1973; Leman 1994; Makoundi et al. 2014; Metcalfe 2002; Richardson 1939; Tan 1984). This belt consists of deep to shallow marine clastic sediments and limestone with predominantly abundance of intermediate to felsic volcanic and volcaniclastic rocks. Central Belt has undergone low grade metamorphism and it was mainly formed during Permo-Triassic activities (Figure 1).

The prolonged exposure during Upper Cretaceous and Paleocene resulted in the eroded post-Triassic successions in Peninsular Malaysia (Clements et al. 2011; Li et al. 2015). The magmatism in the Central Belt are characterized by the alkaline and calc-alkaline series

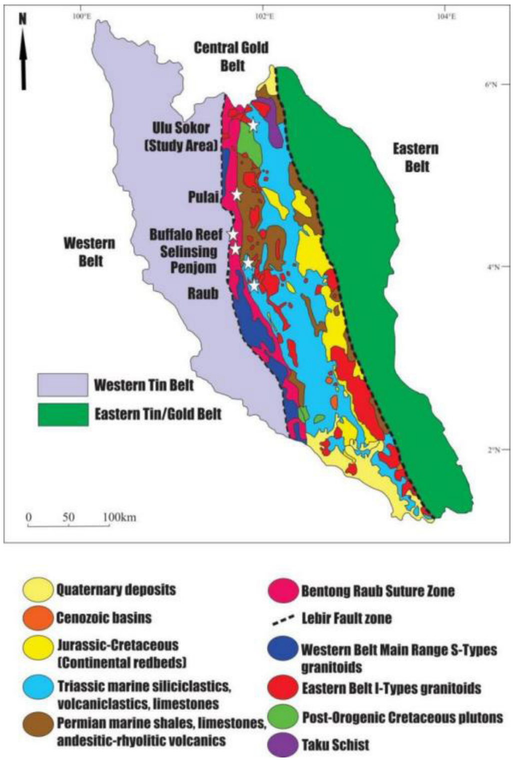

FIGURE 1. The major mineralization belt of Peninsular Malaysia. Note the white star symbol in the map represent the major gold deposit. After (Tate et al. 2009; Yeap 1993)

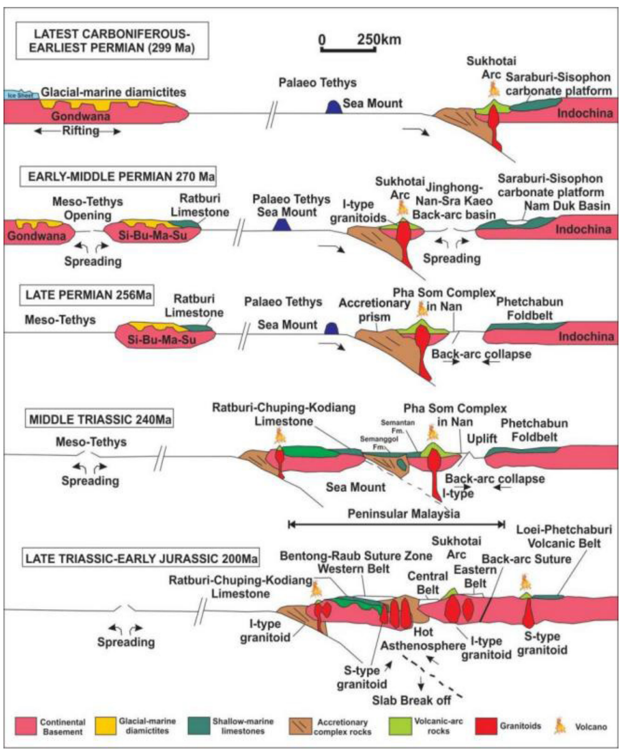

FIGURE 2. The conceptual of formation Bentong-Raub suture zone by the subduction of Palaeo-Tethys ocean and collision of Sibumasu block and East Malaya block (Metcalfe 2002; Ueno & Hisada 1999; Searle et al. 2012; Sone & Metcalfe 2008)

of intrusive Benom Complex. Three new zircon U-Pb ages of igneous rocks from the Benom Complex show the crystallization of diorite and syenite (alkaline series) at 221.8±2.4 Ma and 226.6±3.5 Ma, respectively, and granite (calc-alkaline series) at 207.2±2.0 Ma (Choong et al. 2021).

Volcanics and volcaniclastic are common and significant in the East Malaya Block. Thick piles of volcaniclastics reworked tuffs and agglomerates of Permo-Triassic age occur in the Central Belt of Peninsular Malaysia (Metcalfe 2013b; Metcalfe & Chakraborty 1996), together with products of the Sukhothai arc which is intermediate to felsic volcanic and they were generally younger in age, mainly formed in the Middle Triassic age and considered products of subduction related I-Type granitoids (Ghani 2009).

LOCAL GEOLOGY OF KELANTAN

The Kelantan state is bounded approximately by the latitudes of 5°30’25”-5°10’00” and longitudes of 101°55’30”-102°60’00”. The total area occupied is approximately 15,000 km^2 (Figure 3). The general geology of the Kelantan state consists of three significant types of rocks which are sedimentary, metasedimentary and granitic intrusion rocks (Goh et al. 2006). Permo-Triassic sedimentary and metasedimentary rocks are mainly deposited in the center of Kelantan which comprise of siltstone, shale, slate, phyllite, sandstone, and limestone. The Main Range Granite and Boundary Range Granite are the two main granitic rocks that bordered both Permo-Triassic sedimentary and metasedimentary rocks to the west and east, respectively. Both these intrusions are related to the subduction during Late Triassic to Early Jurassic events (Goh et al. 2006).

There are some windows of granitic intrusion which are Senting Granite, Stong Igneous Complex, and Kemahang Granite within the central part of this state. These belts of granite and country rocks have a north-south trending and it is believed that it is a continuation of the regional geology from north Pahang northwards to the south Thailand (Goh et al. 2006). To the east part of this state, the Boundary Range Granite is overlain by the Quaternary sediments such as coastal alluvial flats of Sungai Kelantan.

The metasedimentary rocks are deposited as a north-south trending which are bordered to the foothills of the Main Range Granite, and they are classified as the oldest rocks in this Kelantan state. It is approximately located at the southwest Kelantan as a Lower Paleozoic sequence. They are mainly meta-pelite with less volcanic fragments and minor arenaceous and calcareous intercalations. On the other hand, amphibolite and serpentinite have been recorded as rare occurrences (Goh et al. 2006; MacDonald 1967).

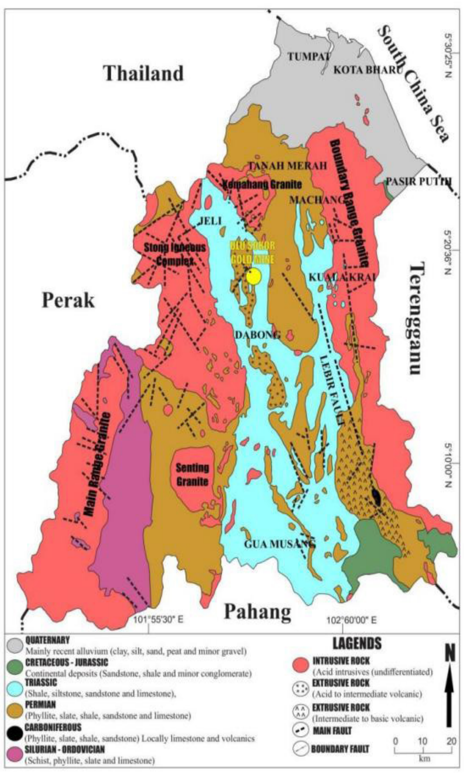

FIGURE 3. The geological map of Kelantan, Peninsular Malaysia (Pour et al. 2017; Teoh et al. 1987)

To the east of Kelantan, Permian volcanic-sedimentary rocks occur widespread and they are overlying unconformably. Triassic rocks which are mainly argillo-arenaceous sediments with intercalated volcanic, and limestone are distributed within the central-south of Kelantan. In addition, several Permian rocks are exposed through this veneer of Triassic sediments (Goh et al. 2006; MacDonald 1967). The youngest rock in this state is Jurassic-Cretaceous which overlies the Boundary Range Granite and Triassic sediments. They are deposited between the boundary of Kelantan, Terengganu and Pahang states. This sequence consists of a conglomerate overlain by sandstone with sporadic volcanic intercalations (Goh et al. 2006; Rishworth 1974).

CENTRAL GOLD BELT OF PENINSULAR MALAYSIA

The contribution of extensive tectonic deformation, metamorphism, magmatism, and fluid flow in Peninsular Malaysia play a role in driving the formation of mineralization deposit. The deposition of mineralization in Peninsular Malaysia is widespread such as base metal and precious metal. According to this study, the gold mineralization deposits are largely found in Central Belt of Peninsular Malaysia. It is mined from quartz lode and stockwork deposits which is mostly associated with the accretionary prism due to the formation of Bentong-Raub suture zone (Ariffin 2012).

The Central Belt of gold mineralization in Peninsular Malaysia is generally developed in the area of low grade metamorphic rock. It took place in the area of metasedimentary and volcanic rocks terrain which was formed during the collision of Sibumasu Block and East Malaya Block. This area was associated by the widespread of deformation system such as brittle, ductile, and shearing system zone. Consequences of the metamorphism and magmatic process in this area created a suitable environment for trap and source of gold mineralization (Ariffin 2012).

According to Wan Hassan and Purwanto (2002), the deposit type of primary gold mineralization in Central Belt of Peninsular Malaysia can be divided into three; which are quartz vein, massive sulphide, and skarn. However, the most prominent type of gold mineralization in this belt is quartz veins. Two styles of gold mineralization were recognized which are gold with sulphide minerals and gold with base metal and carbonate vein. Gold mineralization in quartz veins is distributed from Batu Melintang, Panggung Lalat in Kelantan, through Tersang, Selinsing, Kecau Tui, Penjom, and Raub in Pahang to Gunung Ledang in Johor (Wan Hassan & Purwanto 2002). In terms of the properties of fluid inclusion, structural control and geological setting, these characteristics are consistent with the orogenic gold deposit classification (Groves et al. 1998).

GEOLOGY OF ULU SOKOR GOLD DEPOSIT

The geology of the area is dominated by felsic to intermediate volcanic rocks that occur within an extensive area of marine clastic and argillaceous sedimentary rocks (Goh et al. 2006; Li et al. 2011, 2010) (Figure 4). These volcaniclastics are predominantly tuff and pyroclastics with occasional rhyolitic to dacitic lava, agglomerate, and tuff breccia (Li et al. 2011, 2010). The lithologies present at the Ulu Sokor deposit are Permian metasedimentary and Triassic sedimentary rocks that mainly consist of phyllite, rhyolitic crystal tuff, slate, shale, limestone and interbedded sandstone, siltstone, shale, respectively (Ariffin 2012; Ariffin & Hewson 2007).

Ulu Sokor area is primarily underlain by a Permian lithologies (Figure 4) such as phyllite, tuffaceous phyllite, carbonaceous phyllite, slate, shale, and limestone with widespread of volcanics. However, phyllite covers most of the mining area and is interbedded mainly with rhyolite, slate, shale and less commonly with Permian limestone (Li et al. 2015). The Triassic lithology (Figure 4) mainly consist of interbedded sandstone, siltstone, and shale with lesser amounts of volcaniclastics (Ariffin 2012). According to these lithologies present, it shows that overall mining area is undergone low grade metamorphism.

The lithology in this area are highly folded and observed various dip angles due to geological structure. According to the Li et al. (2015), the main structural feature in the Ulu Sokor area is a series of major N/S-striking folds and faults and ENE–SWW and NW–SE oriented faults. The Permian–Triassic E/W regional compression activity and normal faults that formed in the Central Belt was contributed for the N/S-striking folds and faults in the Permian metasedimentary rocks (Li et al. 2015, 2011). In addition, Li et al. (2015, 2011) indicate the formation of ENE- and NW-trending faults in the Pre cambrian metasedimentary rocks and Triassic sedimentary rocks most probably appear due to Late Triassic–Jurassic compressional tectonics activity.

These two sets of folds and faults may correspond to two episodes of folding and uplift that occurred in Peninsular Malaysia. The major N–S trending faults are interpreted as the oldest structures and are related to oblique amalgamation of Sibumasu Block and the East Malaya Block during the Permian–Triassic, and the ENE- and NW-trending faults are interpreted to be Late Triassic to Jurassic in age (Metcalfe 2013b).

Quartz-dominant vein systems with sulphides and carbonates make up the gold mineralization. There were three stages of hydrothermal alteration and mineralization: (I) silicification and brecciation; (II) carbonatization, sericitization, and chloritization; and (III) quartz–carbonate veins (Li et al. 2015).

MATERIALS AND METHODS

A total of 23 ore samples were collected and marked using GPS (Garmin 64s) from the outcrops of the southern part of Ulu Sokor gold deposit. Ore samples were crushed and pulverized with an agate shatter box at the University of Malaya, as well as polished sections for ore microscopy. The pulverized ore samples were then analyzed for geochemical that include major, trace and rare earth elements by ACME Analytical Laboratories, Vancouver, Canada. Ore microscopy studies on ore samples were performed by optical examination of polished sections using reflected light microscopy (Carl Zeiss Axioplan). A comprehensive explanation of the major, trace and rare earth elements techniques was recorded by Akinola et al. (2021) and James et al. (2021). In addition, another 0.5 g was digested by Aqua Regia technique and analysed by ICPMS to determine the precious and base metal elements. Two g sample were used in carbon and sulphur analysis for determining the amount of carbon and sulfur present in metal-bearing ores.

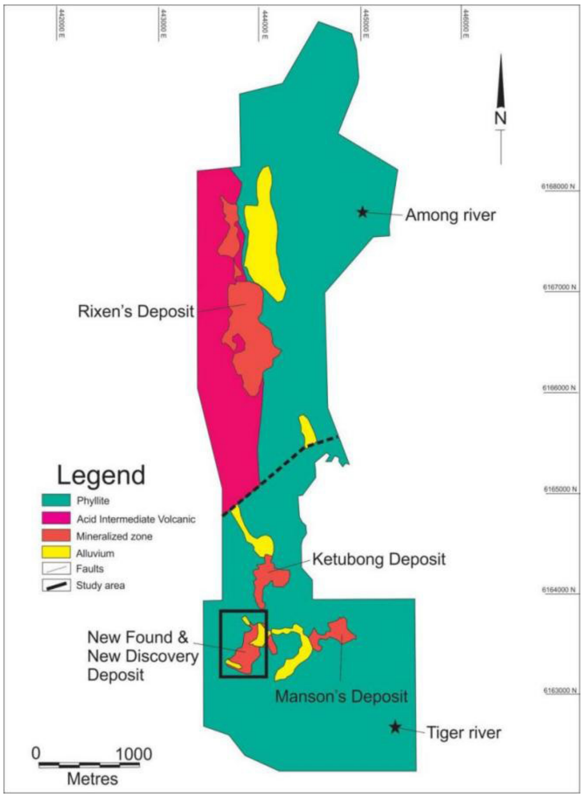

FIGURE 4. The geological and deposit map of Ulu Sokor gold mine, Peninsular Malaysia

RESULTS AND DISCUSSION

MINERALOGY OF ORE ROCK

The mineral assemblages in ore rock are studied in detailed in order to understand the nature and distribution pattern of gold mineralization as shown in (Figure 5). The quartz, ankerite, sericite, chlorite, talc, illite, smectite, epidote, calcite, kaolinite, and sulphide make up the hydrothermal assemblage (Li et al. 2015). The quartz–sulfide veining and quartz–carbonate–sulfide veining systems are both linked to gold mineralization, and gold-bearing sulphide minerals inhabit fractures and interstitial spaces (Li et al. 2015). Early quartz is corroded and replaced by carbonates in most cases, resulting in barren veins (Li et al. 2015). Sulphides were deposited mostly in late generation fractures in late quartz or quartz–carbonate veins. Fracturing, the development of intragranular microfractures in grains and subgrains, changes in veinlet thickness, variable intensity undulatory extinction of quartz, dynamic recrystallization, the porphyroclast system, and the S–C fabric all point to a complicated brittle–ductile deformation history (Li et al. 2015).

After an early stage of ductile deformation that leads to the formation of extensive foliation, such as in phyllite, the paragenetic sequence of mineralization commences. However, silicified rhyolites and phyllite that are invaded by quartz-carbonate veins experience localised ductile deformation. Following this action, a series of hydrothermal events ensued that transported silica-rich fluid into the dilatant zone (Ariffin & Hewson 2007).

Native gold

Gold dominantly occurs as inclusion with bismuthinite. Gold also associated within fractures of other sulphide minerals such as galena, arsenopyrite, chalcopyrite, sphalerite and pyrite in decreasing order of abundance (Figure 5(b) and 5(c)). However, gold is also observed as inclusion with bismuthinite along the quartz veins. In term of grain size occurrences, the gold is normally observed as fine grains with size ranging from 10 μm to 20 μm.

Pyrite

Based on the microscopy studied, the pyrite grain is not co-existing together with the gold, most of the pyrite grain is formed individually. Pyrite seems to be formed at the early and late stage based on the anhedral to euhedral shape. Angular subhedral pyrite grain is enclosed by bismuthinite bearing gold (Figure 5(c)).

Arsenopyrite

Arsenopyrite seems to be formed later than pyrite and it occurs as fine to coarse grains or aggregates with various sizes ranging from 100 μm to 500 μm. The shape is predominantly formed as euhedral to subhedral with some are fractured or brecciated (Figure 5(b), 5(c) & 5(d)). The most common association, which is interstitial gaps in arsenopyrite aggregates, is bismuthinite carrying gold.

Sphalerite

Sphalerite is formed earlier than chalcopyrite and galena. It occurs as fine to coarse grains or aggregates with size ranging from 50 μm to 100 μm. However, it can also observed as fracture infilling and interstitial spaces in arsenopyrite, chalcopyrite, and galena. Sphalerite appear as chalcopyrite disease and are somewhat rimmed on the galena (Figure 5(a) and 5(b)).

Chalcopyrite

Chalcopyrite is formed later than sphalerite. It occurs as a fine grain and it infills the interstitial spaces and fractures within sulphide and quartz veins. Some of the chalcopyrite occurs in the form of disease in the sphalerite. Sphalerite can also be seen replacing and corroding chalcopyrite (Figure 5(a)). Chalcopyrite can be closely associated with gold bearing bismuthinite because the latter occurs as an inclusion in chalcopyrite aggregate.

Galena

Galena is formed later than chalcopyrite and sphalerite. The shape and distribution occurrences are as coarse grains or aggregates and fracture infillings within sulphide and quartz veins. The size observed varies from 100 μm to 500 μm. Galena is often seen closely related or associated with bismuthinite (Figure 5(b) and 5(c)). Bismuthinite can be observed as inclusions in the galena. Bismuth-gold can also be observed infilling the cracks and fractures of galena.

Bismuthinite

Bismuthinite is always dominantly associated with gold, and it is closely associated with other sulphide minerals such as galena, arsenopyrite, chalcopyrite, sphalerite, and pyrite in descending order of abundance. However, it can be observed along the quartz vein without any contact with other sulphide minerals (Figure 5(d)). In terms of shape, the bismuth observed is in the form of anhedral with size ranging from 50 μm to 300 μm. It seems to be formed later than other sulphide minerals.

Covellite

Covellite occurs as infilling the fractures in chalcopyrite (thin veinlets). Its origin is attributed to supergene alteration of chalcopyrite (Figure 5(a). Covellite have a features of anhedral shape and showing a bluish color under microscope.

The paragenetic sequence of ore minerals in the southern part of Ulu Sokor gold deposit is shown in Table 1.

Based on the data from mineralogy part, it shows that the significant visible gold mineralization type in southern part of Ulu Sokor gold deposit is gold-bismuthinite (Au-Bi_2S_3).

TABLE 1. The paragenetic sequence of ore mineralization at southern part of Ulu Sokor gold deposit

	Early	Middle	Late	Secondary
		Ductile deformation		
Early quartz	------------------	--		
Early carbonate	------------------	--		
Pyrite	--------------	-------		
Arsenopyrite	-----------	-------		
		Brittle deformation		
Late quartz		------------------	--	
Late carbonate		------------------	--	
Sphalerite		------------	---------------	
Chalcopyrite		-----------	--------	
Galena			------------	
Native gold			------------------	
Bismuthinite		---------	------------------	
		Supergene		
Covellite				------------------

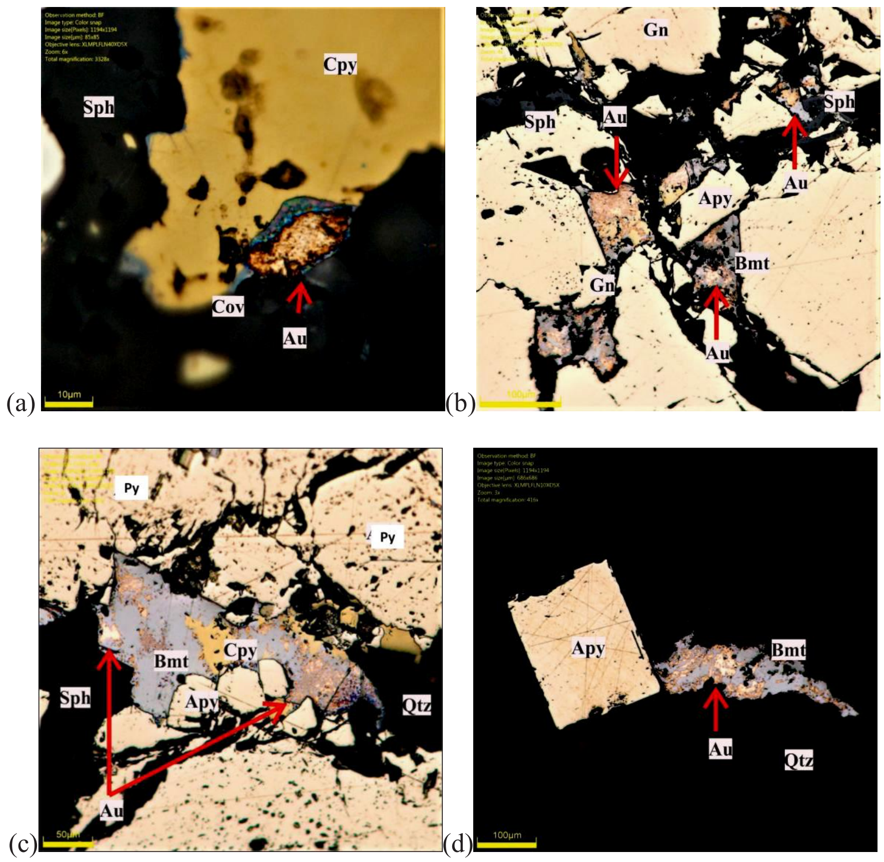

FIGURE 5. Photomicrograph of reflected light (plane light) for ore rock at southern part of Ulu Sokor gold deposit. (a) Anhedral chalcopyrite which associated by gold is enclosed by sphalerite. Covellite is at the boundary of chalcopyrite (b) Subhedral to anhedral of galena and arsenopyrite grained is associated together by infilling of bismuthinite bearing gold in the fractures. Some galena is enclosed by sphalerite. (c) Pyrite is partly enclosed to arsenopyrite and bismuthinite bearing gold. Bismuthinite bearing gold is enclosed by sphalerite. (d) Subhedral coarse grained arsenopyrite in quartz vein. Gold associated with bismuthinite in quartz vein

BULK ORE CHEMISTRY

The 23 bulk ore rock samples were analyzed for geochemical analysis to determine the relationship or style of gold (Au) with other selected metals (Table 2). Total sulphur, carbon and total iron of ore samples are tabulated in Table 2. The samples were collected from two different pits namely New Found and New Discovery. Based on the relationship of Au with other metals (log Au vs log metal) such as silver (Ag), bismuth (Bi), copper (Cu), lead (Pb), arsenic (As) and zinc (Zn), there are less significant differences in between these two pits (Figure 6). These selected elements were chosen based on the significant enrichment observed in the ore samples.

TABLE 2. Trace element, total sulphur, carbon and total iron composition ores sample at southern part of Ulu Sokor gold deposit

Element	Au	Ag	Bi	Cu	Pb	As	Zn	Sb	S	C	Fe_2O_3	Coordinates (West Malaysian Grid)
Unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	%	%	%	
d.l.	0.0005	0.1	0.1	0.1	0.1	0.5	1	0.1	0.02	0.02	0.04	
Sample												
NF1	29.7662	4.4	>2000.0	701.9	205.6	187.7	8	8.2	34.25	0.04	47.51	QU 443655 613283
NF30	17.8770	91.5	>2000.0	1709.3	6551.1	279.7	627	73.5	19.28	0.09	27.56	QU 443644 613278
NF36	16.1187	21	1252.7	4189.2	498.6	669.8	233	3.8	24.23	0.06	58.8	QU 443650 613285
NF2	5.9893	2.2	603.1	512	59	160.9	160	2.3	7.3	0.09	13.92	QU 443643 613281
NF31	5.6014	2.6	108.8	110.7	19	63.4	11	1.3	38.83	0.03	54.23	QU 443600 613291
NF7	5.0909	0.5	10	35	63.5	4.4	50	<0.1	0.06	0.03	6.78	QU 443540 613259
NF5	1.2203	0.4	12.2	368.7	45.9	9	4	0.3	0.04	0.05	9.83	QU 443563 613312
NF25	0.6679	0.4	8.2	10.7	22.1	25.9	28	0.1	2.45	0.18	5.45	QU 443753 613205
NF14	0.5251	6.8	18.1	58.1	20.1	132.7	6	0.4	9.78	0.02	15.35	QU 443629 613266
NF3	0.2276	5.4	34.8	2927.7	13.3	78.7	145	7.1	19.27	0.09	30.19	QU 443611 613284
NF15	0.1603	0.2	49.3	203.8	28.6	13.4	10	0.4	0.07	0.04	6.41	QU 443629 613266
NF27	0.1089	0.2	129	112.2	137.8	29	115	1.3	0.3	1.45	6.16	QU 443742 613230
ND25	28.6142	0.7	707.9	17.8	21.5	16.6	16	1.1	19.2	0.04	27.91	QU 443878 613562
ND13	20.3347	3	113.3	40.7	18.4	22.5	7	4.2	3.17	0.08	8.98	QU 443944 613627
ND12	10.7645	39.1	1759.8	131.5	47.4	207.6	15	67.6	37.33	0.07	50.8	QU 443945 613613
ND11	4.59	2.2	47.1	92.1	39.1	106.7	25	1	40.7	0.03	54.63	QU 443943 613597
ND10	3.0621	2.3	191.1	166.7	9.1	55.6	7	3.1	21.69	0.07	28.59	QU 443945 613582
ND9	1.3951	2.4	90.7	491.8	60.5	124.1	74	19	9.65	0.17	18.23	QU 443946 613579
ND21	0.5777	0.9	68.9	62.7	245.8	32	87	1.1	0.05	0.33	5.99	QU 443900 613512
ND22	0.5294	0.3	45.1	162.3	112.1	26.7	48	0.6	0.11	0.1	8.92	QU 443900 613512
ND17	0.5191	8.8	116.6	36.5	85.8	96.1	9	1.5	41.29	0.04	53.71	QU 443927 613555
ND14	0.4435	1.4	38.1	25.2	18.6	76.4	12	0.7	12.35	0.21	17.74	QU 443950 613642
ND29	0.1157	0.2	41.9	76.4	10.7	10	54	0.3	2.76	0.05	8.23	QU 443870 613606

Note that d.l. is detection limit

As shown in the variation diagrams, most of the selected metals show a flat trend with correlation coefficient in range of 0.91 to 0.34 and 0.43 to 0.12 for both New Found and New Discovery, respectively. However, some of the samples show highly enriched such as Bi (NF1>2000 ppm and NF30>2000 ppm) and Pb (NF30 = 6551.1 ppm).

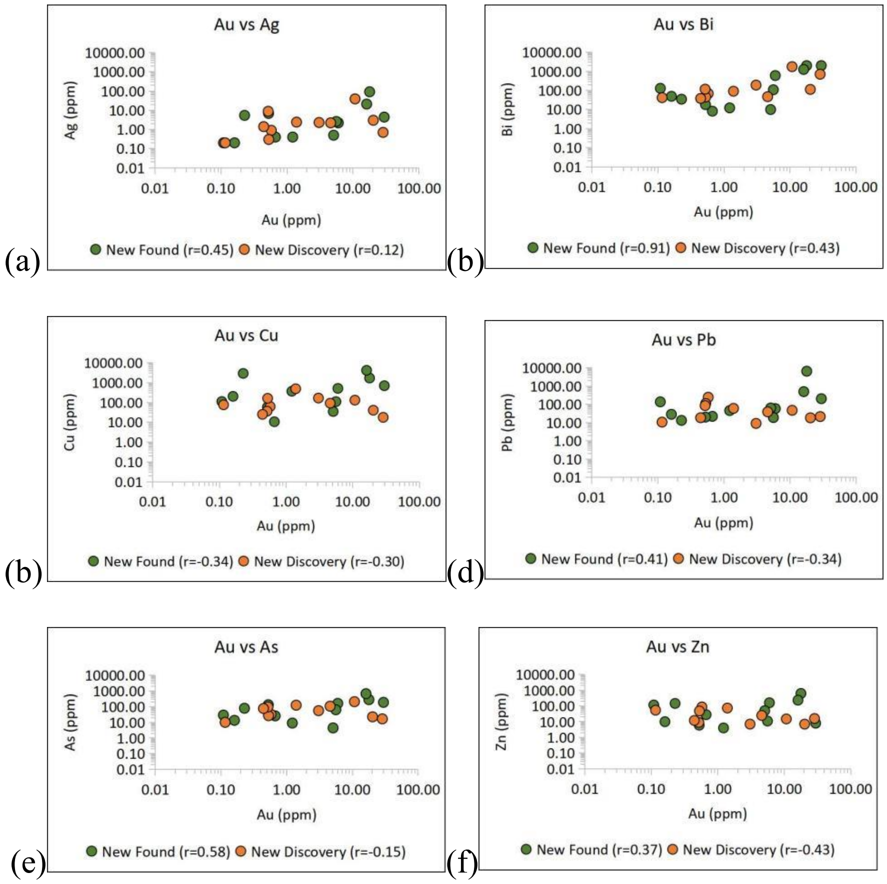

FIGURE 6. (a) to (f) Variation diagram of Au versus selected metal (Ag, Bi, Cu, Pb, As, and Zn) ore rocks at southern part of Ulu Sokor gold deposit. Unit: part per million (ppm)

Selected log metal abundance versus log cumulative probability is plotted in order to determine the probability distribution pattern of Au, Ag, Bi, and Cu as shown in Figure 7 and Pb, As, and Zn in Figure 8. Furthermore, the geometric mean value is utilised to calculate the average mean concentration within a large set of data. The geometric mean value of ore rock samples for Au is 1.9 ppm with n=23, Ag is 2.6 ppm with n=19, Bi is 96 with n=22, Cu is 148 ppm with n=23, Pb is 55 ppm with n=23, As is 53 ppm with n=23 and Zn is 31 ppm with n=22.

Either as lattice-bound particles or as native gold nanoparticles, refractory gold might exist in pyrite. The mechanism of refractory gold occurrence in pyrite can be characterized by the Au/As molar ratio (Reich et al. 2005). Refractory gold occurs as lattice-bound particles if the Au/As molar ratio is less than 0.02, whereas a ratio greater than 0.02 indicates the presence of nanoparticles. The Au/As molar ratios in pyrite are predominately lower than 0.02 based on 69 samples geochemical study in the southern part of Ulu Sokor gold deposit. Refractory gold may thus be a lattice-bound form of native gold. Similar to already published evidence for arsenian pyrite in several orogenic, epithermal, and deposits of gold of the Carlin type typically have the highest concentrations of unnoticeable gold (Basori et al. 2018; Large et al. 2009; Reich et al. 2005).

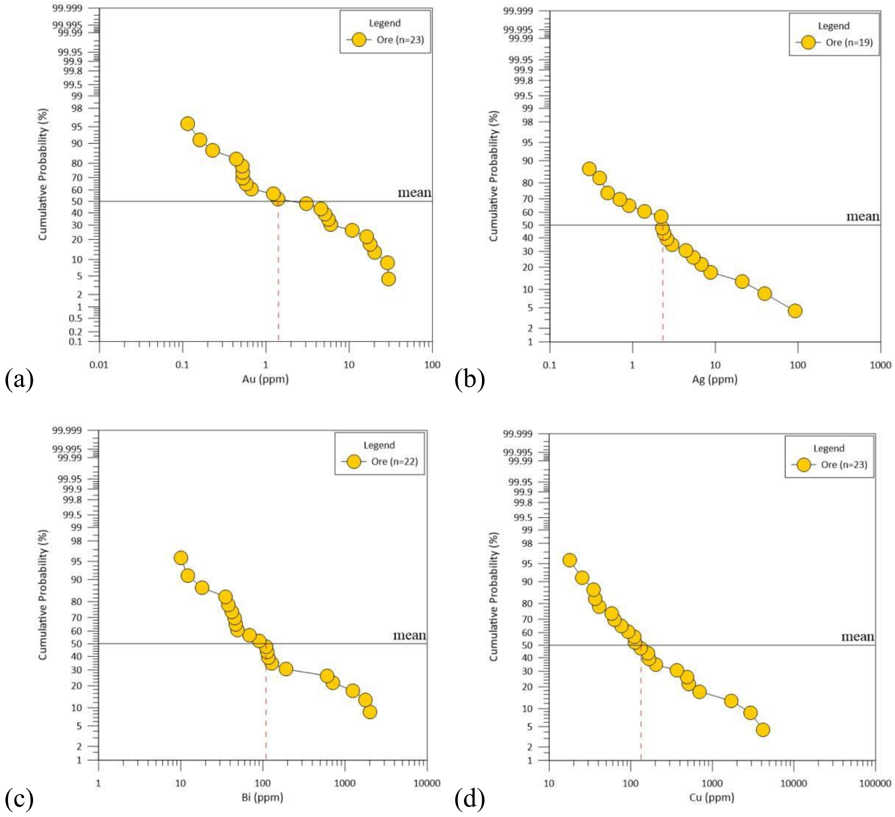

FIGURE 7. (a) to (d) Variation diagram of selected metal (Au, Ag, Bi, and Cu) abundance versus cumulative probability of ores rock at southern part of Ulu Sokor gold deposit. Unit: part per million (ppm)

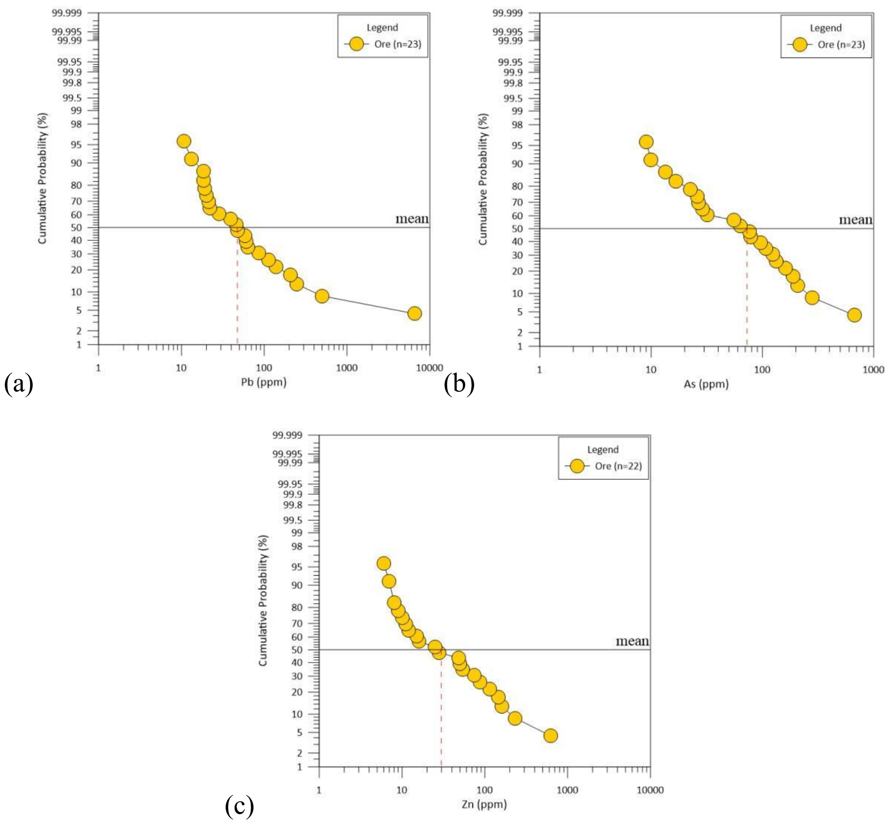

FIGURE 8. (a) to (c) Variation diagram of selected metal (Pb, As and Zn) abundance versus cumulative probability ores rock at southern part of Ulu Sokor gold deposit. Unit: part per million (ppm)

Conclusion

Gold mineralization is primarily hosted in structurally controlled quartz vein which occurs in various degrees of ductile-brittle environment. Based on the field relationships, ore microscopy and geochemical data analysis, there are two main gold mineralization type in the southern part of Ulu Sokor gold deposit:

(1) Gold associated and as inclusions in bismuthinite based on the mineralogy study.

(2) Refractory gold occurs as lattice bound in pyrite based on the Au/As molar ratio.

In terms of mineral exploration and gold prospecting, the significant enrichment in this study area is Bi. However, some other metals can also be considered as a significant value in this area such as Pb, As, Cu, and Zn. From the bulk ore chemistry, the geometric mean values of Au and Bi are 1.9 ppm Au (n=23) and 96 ppm Bi (n=22), respectively.

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