http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 04 No 02 2019

RESEARCH ARTICLE

Alteration, Mineralization and Geochemistry of Metamorphic Rocks Hosted Hydrothermal Gold Deposit at Rumbia Mountains, Bombana Regency, Southeast Sulawesi, Indonesia

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Received: Nov 11, 2018; Accepted: May 30, 2019.
DOI: 10.25299/jgeet.2019.4.2.2346

Abstract

In Indonesia, gold is commonly mined from porphyry, epithermal and skarn type deposits that are commonly found in volcanic/magmatic belts. However, were recently numerous gold prospects discovered in association with metamorphic rocks. This paper is intended to describe an alteration and ore mineralogy hosted by metamorphic rocks at Rumbia mountains, Bombana regency, Southeast Sulawesi province, Indonesia. The study area is found the placer and primary gold hosted by metamorphic rocks. The placer gold is evidently derived from gold-bearing quartz veins hosted by Pompangeo Metamorphic Complex (PMC). This study is conducted in three stages, three stages including desk study, field work and laboratory analysis. Desk study mainly covers literature reviews. Field work includes mapping of surface geology, alteration and ore mineralization as well as sampling of representative rocks types, altered rocks and gold-bearing veins. Laboratory analysis includes the petrologic observation of handspecimen samples, petrographic analysis of the thin section and ore microscopy for polished section, XRD (*X-ray diffraction*), ICP-AES (*Inductively Coupled Plasma Atomic Emission Spectroscopy*), ICP-MS *(Inductively Coupled Plasma Emission Mass Spectrometry* and FA/AAS (*Fire Assay/Atomic Absorbtion Spectophotometry)* analysis. The results shows that the alteration characteristics of hydrothermal gold deposits in Mendoke and Rumbia mountain consist of 3 (three) alterations namely sericitic, argillic dan propylitic. Characteristics of mineralization hydrothermal gold deposits in the research area are generally p related to gold-bearing quartz veins/veinlets consist of chalcopyrite, pyrite, chrysocolla, covellite, cinnabar, magnetite, hematite and goetite in rocks categorized into greenschist facies. There are three generations of veins identified including the first is parallel to the foliations, the second crosscut the first generation of veins/foliations, and the third is of laminated deformed quartz+calcite veins at the late stage. The quartz veins commonly deformed, segmented, massive, laminated, irregular, brecciated, and occasionally sigmoidal. The veins contain erratic gold in various grades from below detection limit <0.0002 ppm to 18,4000 at found in third generation veins which are laminated quartz±calcite in argillic alteration. ppm. The protoliths of metamorphic rocks in Rumbia Mountain, which comes from sedimentary rocks, spesifically pelitic rocks and graywacke. Based on those characteristics, it obviously indicates that the primary gold deposit present in the study area is of orogenic gold deposits type. The orogenic gold deposit is one of the new targets for exploration in Indonesia.

Keywords: Alteration, Ore Mineralogy, Hydrothermal Gold Deposit, Metamorphic Rocks, Rumbia Mountains, Southeast Sulawesi.

1. Introduction

Gold has had an impact on the everyday economic activities of ordinary people since at least Egypt in 1400 BC, where it was used as a monetary standard. Perhaps the most famous usage of gold was as money under various gold standards.

Gold is one metal of the most malleable, ductile, dense, conductive, nondestructive,brilliant, and beautiful ofmetals. This unique set of qualities has made it a coveted object for most of human history in almost every civilization (O'Connor *et al*., 2015). Based on this, many researchers and mining companies are trying to find gold reserves to explore. Commonly, gold is mostly mined in Indonesia from hosted by vulkanic rocks including porphyry, epithermal, and skarn type deposits that are commonly found in volcanic belts along island arcs or active continental margin settings. Several gold deposits were discovered are Batu Hijau in Sumbawa Island Island (Idrus *et al*., 2007; Imai & Ohno, 2005) and Grasberg in Papua including porphyry type; Pongkor in West Java Java (Warmada, 2003), Gosowong in Halmahera Island including epithermal type and Ertsberg, Kucing Liar, Deep Ore Zone (DOZ) in Papua including skarn type. In Sulawesi Island, gold is also predominantly related to volcanic rocks, which are extended along western and northern

Neogene magmatic arcs of the island island (Idrus, 2009) (Fig. 1).

However, were recently in gold exploration activities are not only focused along volcanic-magmatic belts, but also starting to shift along metamorphic and sedimentary terrains because numerous gold prospects discovered in association with metamorphic and sedimentary rocks. Several primary gold deposits were discovered with metamorphic rocks for instance, Langkowala area and Wumbubangka mountaints, Bombana in Southeast Sulawesi (Idrus & Prihatmoko, 2011; Idrus, *et al.*, 2011; Idrus *et al.*, 2012), , Awak Mas in South Sulawesi; Poboya LS- epithermal in Central Sulawesi (Wadji et al., 2011) and Gunung Botak in Buru Island, Mollucas (Idrus *et al.*, 2014). Gold-bearing quartz veins are also recognized in Derewo metamorphic belt at northern and northwestern part of Central Range Papua. Some exploration reports categorized the Derewo metamorphic-related quartz veins into mesothermal gold deposit type (Idrus *et al.*, 2014).

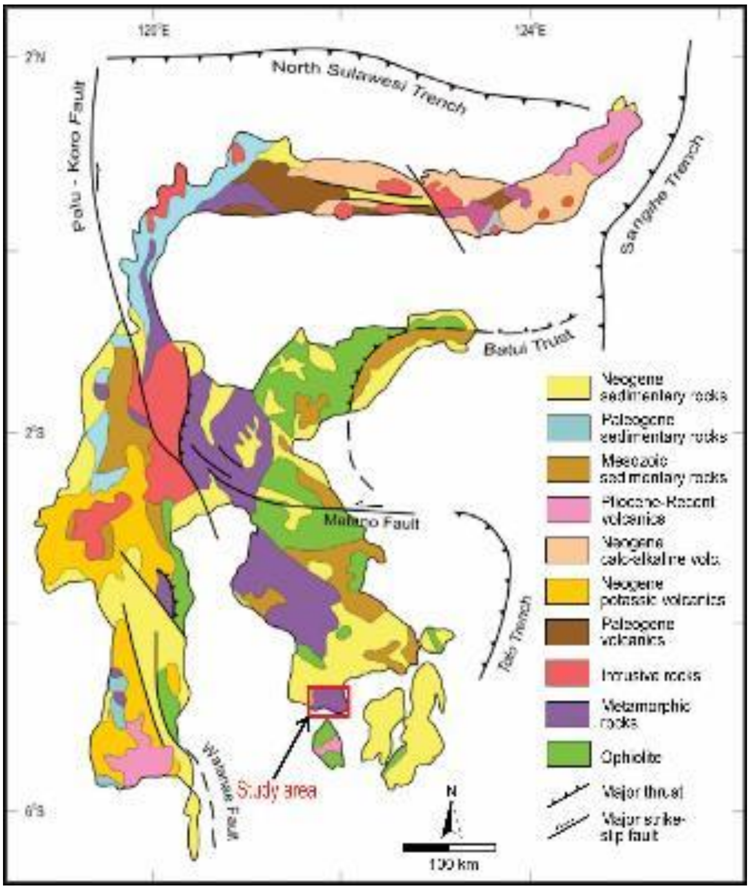

Fig. 1. Geological setting of Sulawesi Island and location of the study area in Rumbia mountains (squared area), Southeast Sulawesi (modified from Leeuwen and Pieters, 1992).

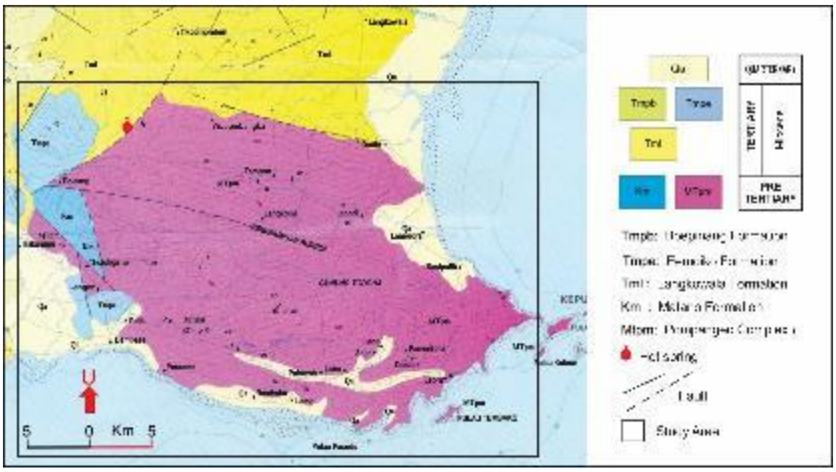

Fig. 2. Geological Geological map of Rumbia mountains area occupied by Paleozoic metamorphic rocks (Pompangeo Complex; Mtpm) (Modified from Simandjuntak *et al.*, 1993). Squared area indicates the location area of this study.

The gold mineralization genetically occurs in association with sedimentary rocks is Paningkaban, Banyumas Regency, Central Java (Idrus *et al*., 2015). Rumbia mountains area is located in the Bombana Regency of Southeast Sulawesi, Indonesia (Fig. 2). This research aims to explore the alteration and ore mineralogy of metamorphic rocks hosted hydrothermal gold deposit at Rumbia mountains by the application of petrographic, ore microscopy and XRD (*X-ray diffraction*), ICP-AES (*Inductively Coupled Plasma Atomic Emission Spectroscopy*), ICP-MS *(Inductively Coupled Plasma Emission Mass Spectrometry*) and FA/AAS (*Fire Assay/Atomic Absorption Spectrometry)* analysis.

This study is an important stage for the next exploration of gold in the area or other areas that have an identical setting of geology. Metamorphic rock-hosted gold deposits could represent the new targets for gold exploration particularly in Indonesia.

2. Geological Setting

The stratigraphy in the southeastern arm of Sulawesi consists of three constituent rocks are Sulawesi Molasse composed of clastic sediments and carbonate, ophiolite complex are dominated by mafic and ultramafic rocks and continental terrain composed of metamorphic rocks. Contacts between the ophiolite complex and continental terrain, including their basement rocks are faulted. The Sulawesi Mollase unconformably overlies both the ophiolite complex and continental terrain. The mountains Rumbia is a part of continental terrain is subsequently occupied by metamorphic rocks (Pompangeo Complex, Mtpm) consisting of mica schist, quartzite, glaucophane schist and chert. The continental terrain, which was first described by Surono, 1994. The metasediments and metamorphic rocks are of Permian-Carboniferous in age and occupy the Mendoke and Rumbia Mountains. Mica schist and metasediments particularly meta-sandstone and marble are commonly characterized by the presence of quartz veins various width up to 2 meters, containing gold in some places (Idrus *et al*., 2011).

The Langkowala Formation is unconformably underlain by Paleozoic metasediments and metamorphic rocks (Pompangeo Complex, Mtpm) and conformably overlain by the Eemoiko Formation (Tmpe), which is composed of corraline limestone, calcarenite, marl and sandstone; and Boepinang Formation (Tmpb), which is composed of sandy claystone, sandy marl and sandstone. The Eemoiko and Boepinang Formations were reported having Pliocene age (Surono, 2013).

3. Research Methods

Field investigation was carried out in Rumbia mountains area of Southeast Sulawesi. The samples consist of altered rock, veins and clay samples collected from different hydrothermal alteration zones and ore samples.

This study is conducted in four stages including fieldwork, laboratory analyses, data analyses and interpretation. Fieldwork includes mapping of surface geology, alteration and ore mineralization as well as sampling of representative rock types, altered rocks and gold bearing veins. Laboratory work includes slab, vein textural dan structural analyses and mineralogy (petrography, ore microscopy and XRD (X-*Ray diffraction*); rock geochemistry (ICP-AES (*Inductively Coupled Plasma Atomic Emission Spectroscopy*) and ICP-MS *(Inductively Coupled Plasma Emission Mass Spectrometry)*; ore geochemistry or bulk-ore chemistry FA/AAS (*Fire Assay/Atomic Absorbtion Spectrometry)* analysis. The mineralogical analysis was conducted at Department of Geological Engineering, Gadjah Mada University; rock geochemistry and bulk-ore chemistry was done at ALS Global - Geochemistry Analytical Laboratory in North Vancouver, BC, Canada, ALS Canada Ltd in Canada.

4. Characteristics of Quartz Veins

The quartz veins in the study area consist of three generations. The first is parallel to the foliations, the second crosscuts the first generation of veins/foliations, and the third is of laminated deformed quartz+calcite veins at the late stage (Fig. 3).

The texture of quartz veins are mostly sheared/ deformed, irregular vein, brecciated, and relatively massive segmented, laminated in accordance with the criteria of Yilgarn Block orogenic gold deposits in Western Australia, Racetrack West Australia and Sigma Mine in Canada (Groves, 1993; Groves et al., 1998).

Based on data shows that gold-bearing quartz (Qz) veins/veinlets have been discovered in association with Paleozoic metamorphic rocks particularly mica schist, actinolite schist, phyllite and metasandstone which are petrologically categorized into facies of greenschist, where this type of metamorphic facies mostly become the host of orogenic gold deposits in entire world, such as Yilgran Block orogenic gold deposits in Western Australia, Juneau gold belt, Talkeetna Mts south-central, East-central, Seward Peninsula in Alaska, Slave Province, Canada (Groves, 1993; Groves et al., 1998; Goldfarb et al., 2015); and in Wiluna, Racetrack, Mt Charlotte, Golden Mile, Lancefield in Western Australia and in Ross Mine, Kircland Lake, Dome, Canada, Hollinger McIntyre in Canada, Muruntau in Uzbekistan, Morro Velho in Brazil, Ashanti in Ghana, Homestake in USA and Bendigo in Australia , Mother lode in the United States (Groves et al., 1998; 2003; Gebre-Mariam et al., 1995).

5. Characteristic of Hydrothermal Alteration

Hydrothermal alteration and mineralization underlie within all lythologic units found in the research area. Widespread zones of hydrothermal alteration are found on the surface. Alteration is typically pervasive and selective pervasive with intensity ranges from weak to strong, so it is very rare to observe good outcrops in the area. In general, the wallrocks are weakly altered. Strong alteration zone is only restricted surrounding quartz veins (like halos/selvage). Hydrothermal alteration in Rumbia Mountains is determined by surface geological data, petrography analysis, and supported by XRD analysis. The determination of alteration zone in Rumbia Mountain is based on Corbett and Leach, 1997 and Thompson and Thompson, 1996.

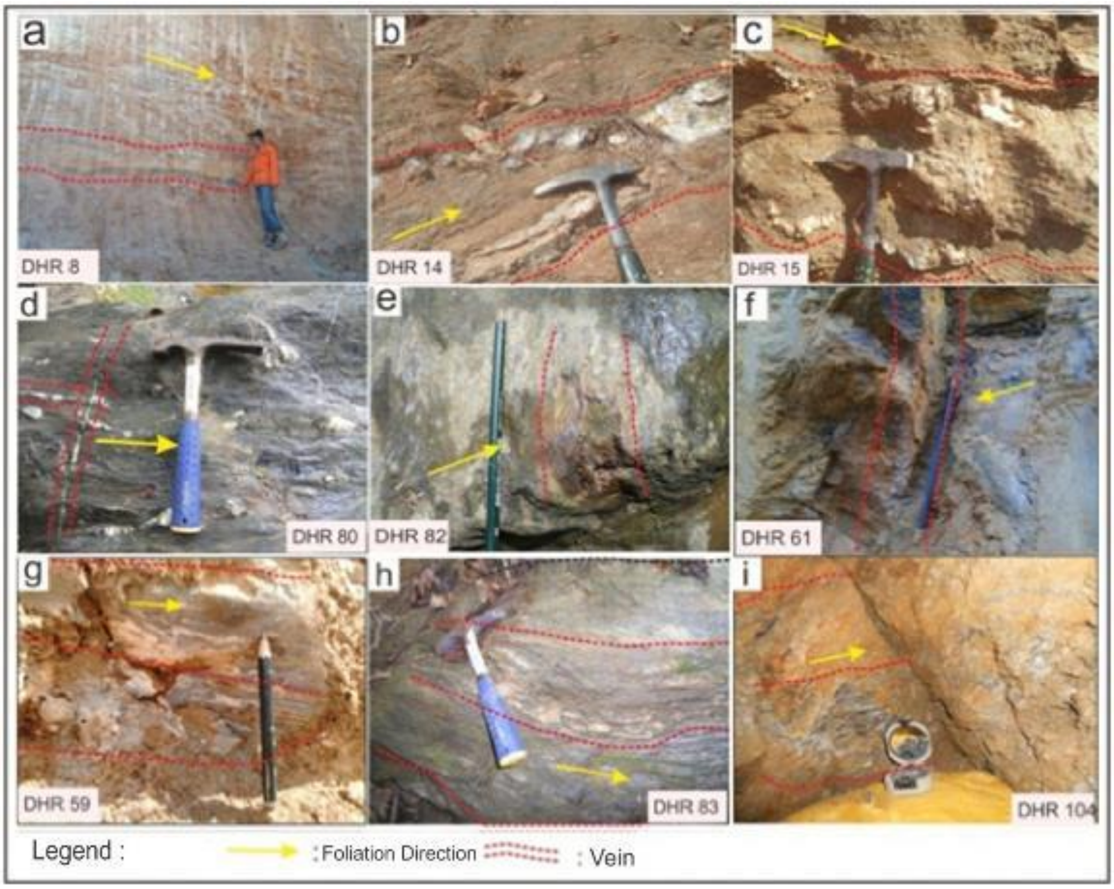

Fig. 3. Characteristics of quartz vein : (a). Brecciated, sheared/deformed quartz vein (first generation) parallel to the foliation, b) massive, crystalline of quartz vein, (first generation) which is parallel to the foliation, c) brecciated, sheared/ deformed quartz vein (second generation) d). irregular vein, sheared/segmented of quartz vein crosscutting foliation (second generation), (e) A cluster of sheared/deformed laminated quartz vein (third generation), (f) laminate quartz vein (third generation).

Hydrothermal alteration in Rumbia Mountains comprises 3 (three) types (Fig. 4), namely sericitic, argillic and prophyllitic alteration. Sericitic alteration is characterized by the presence of muscovite and or sericite-quartz-opaque; argillic alteration is characterized by the presence of clay minerals/clay-quartz-opaq; prophyllitic alteration is characterized by the presence of chlorite-epidote-calcite and others minerals like pyrite and opaque minerals. Clay mineralogy of altered rocks was identified in detail by XRD studies. Based on XRD analysis, the clay at argillic alteration consists of illite and kaolinite minerals. The three alterations were corresponding to Kalgoorlie orogenic gold deposits in Australia, Val d'or in Canada, Ashanti in Ghana and Mother lode in the United States (Groves et al., 1998).

5.1 REE Geochemistry Discrimination

Rare earth elements can potentially be remobilized during alteration, particularly K-silicate (potassic), sericitic, argillic and propylitic alterations (Idrus et al, 2009). REE diagram-chondrite normalized must use the same sample with some variations of alteration to determine the enriched and depleted of REE elements in one type of rock based on the analysis result from ICP-AES and ICP-MS. The patterns show that the REE are depleted with increasing alteration intensity from the least-altered rock (shaded area), through prophyllitic, sericitic and argillic alteration. The value of REE elements in chlorire-schist rock in Rumbia Mountains has a decreasing trend started from prophyllitic alteration, followed by sericitic, and ended by argillic. Characteristics of REE geochemistry Rumbia Mountains has significantly depleted of REE elements in high/total intensity of argillic alteration samples with pervasive texture. The value of REE is commonly depleted together with increasing in alteration intensity (Fig. 5).

The depletion of REE is also closely related to the stability of hydrothermal minerals during alteration. The LREE in the altered rocks of the chlorite-epidote and transitional chlorite-sericite alteration zones, however, are slightly increased which may indicate that epidote and chlorite accommodate the released REE during the breakdown of the primary phases. The sericite altered rocks are commonly enriched in the HREE, due to the ability of sericite and possibly chlorite to absorb the released elements. The argillic altered rocks display the strongest REE depletion, which is explained by the complete breakdown of the primary feldspar and mafic minerals during the alteration.

Fig. 4. Hyrdothermal alteration types : (a,b). Sericitization, (c,d). Argillic, (e,f). propylitic alteration. The scale bar without expression in each of photomicrograph on this paper indicates 1 mm. x-nicol 40x. Opq= opaq, Ms= Muscovite, Ser= sericite, Qz= quartz, Rt= rutil, Gln= glaucophane, Cly=clay,, Chl= chlorite, Ep= epidote,

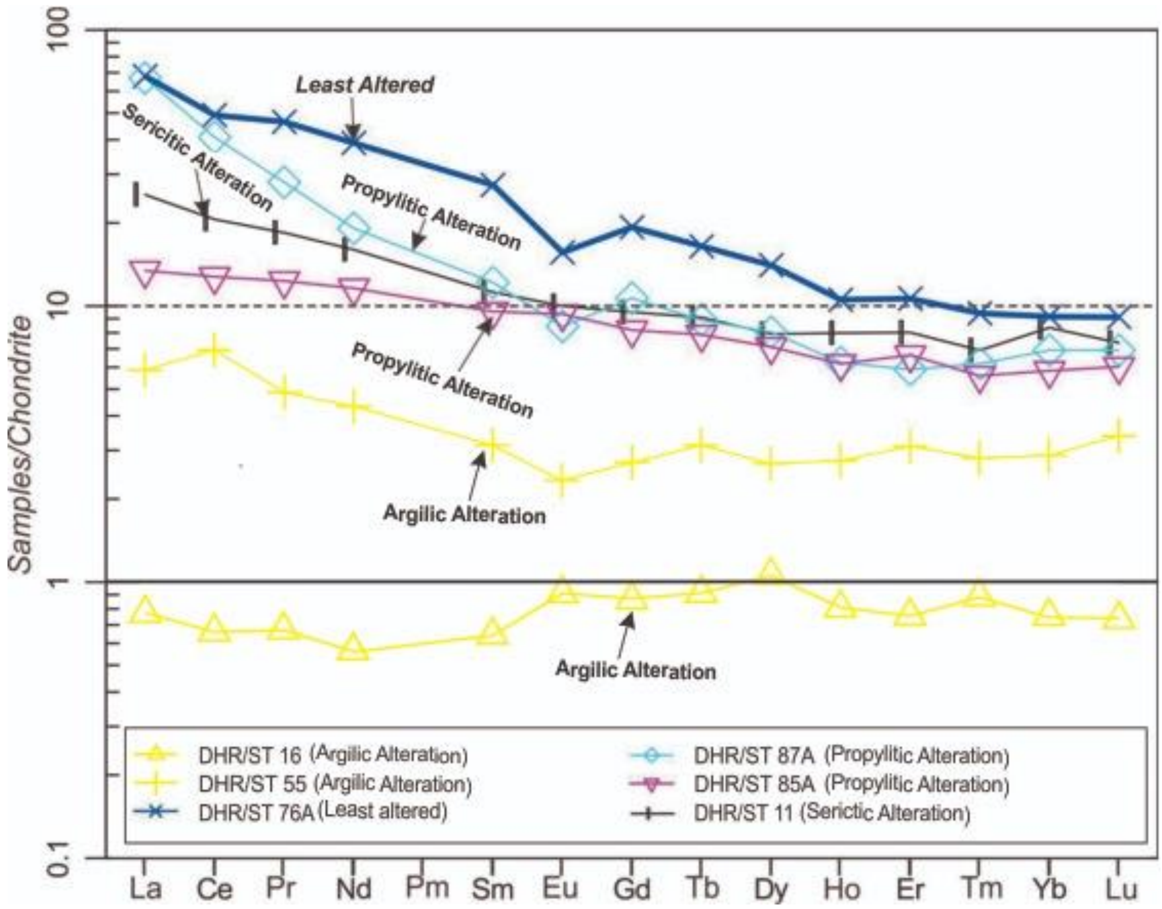

Fig. 5. REE-chondrite normalized patterns discriminating various alteration zones within the Rumbia mountains deposit with respect to the chloritic schist rocks with several alteration zones(Sun & McDonough, 1995).

6. Characteristics of Mineralization

Based on field relationship, ore microscopy, electron microprobe analyses, there some precious metal identified consist of native gold and ore mineralization including pyrite (FeS_2), chalcopyrite ($CuFeS_2$), hematite (Fe_2O_3), cinnabar (HgS), covelite (CuS), chrysocolla ($(CuAl)_2H_2Si_2O_5nH_2O$), sinnabar (HgS), magnetite (Fe_3O_4) and goethite ($FeHO_2$) (Fig. 6) which related to the Yilgarn Block orogenic gold deposits in Western Australia (Groves, 1993). The presence of Sb and Hg in all samples genetically indicates that the orogenic gold deposits in epizonal and mesozonal zones as same as Wiluna deposits, Racetrack, Mt. Charlotte, Golden Mile, Lancefield, in Western Australia and in Ross Mine, Kircland Lake, Dome, in Canada (Groves, 1993; Groves et al., 1998; Gebre-Mariam et al., 1995). Idrus *et al.* (2012) also reported the presence of tripuhyite ($FeSbO_4$) and rare arsenopyrite ($FeAsS_2$) are present in the quartz veins and silicified metamorphic wallrocks. The presence of geological structure is a controlling factor of mineralization, which is southeast-northwest oriented faults and northeast-southwest oriented faults. Gold, stibnite, and arsenopyrite which can not be found in Rumbia Mountain with ore microscope but have minor possibility to be present due to FA/AAS analysis, those are Au = < 0.0002-18.4 ppm; As = 0.69-1,840 ppm; Sb = 0.635-6,170 ppm.

Pyrite, hematite, cinnabar and stibnite are present abundantly in the primary mineralization gold deposits, present in the quartz veins and wallrocks; and commonly present at alteration rocks (Fig. 7). Pyrite occurs as isolated idiomorphic crystals, angular fragmens,, strongly brecciated fragments, anhedral shape, medium reflectance and isotropic. Some pyrite grains are partly enclosed by hematite, chalcopyrite and possibly stibnite. Fractures and brittle cavities in pyrite are often filled by hematite and chalcopyrite. Hematite is typically pinkish orange in color and commonly present in altered rocks, internal purple reflections, subhedral-anhedral crystals, present as sulfide mineral interactions with oxygen causing the oxidation of sulphide minerals, especially pyrite. Hematite is looked replacing pyrite.

Chalcopyrite is associated with pyrite while cinnabar is typically pinkish red in color and commonly occurred in the form of mineralized layers along foliations of the metamorphic rocks. Pyrite, hematite, cinnabar and stibnite are genetically closely related to gold mineralization (Hasria et al., 2017).

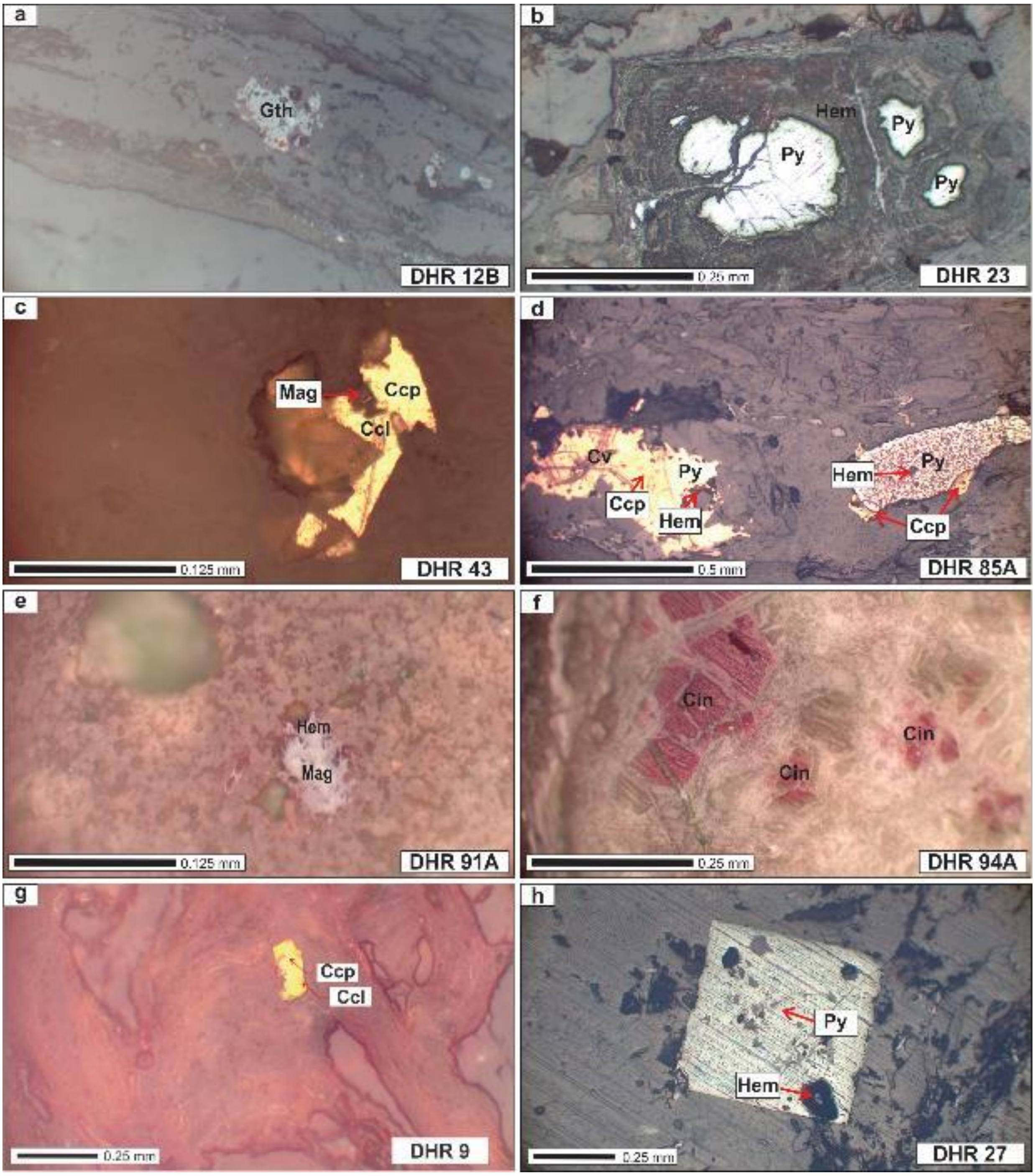

Fig. 7. Ore minerals in study area. a. Goethite. b. Hematite is looked replacing pyrite. c. Chrysocolla is replacing chalcopyrite. d. Chalcopyrite is looked replacing covelite and hematite is looked replacing pyrite. e. Magnetite and hematite. f. The present of abundantly cinnabar in mineralization of hydrothermal gold deposits. g. Chrysocolla is replacing chalcopyrite. h. Hematite is looked replacing pyrite. Goethite. The scale bar without expression in each of photomicrograph on this paper indicates 1 mm. Py= pyrite, Ccp= chalcopyrite, Hem= hematite, Cin= cinnabar, Gth= goethite, Mag = magnetite, Ccp= chalcopyrite, Ccl = chrysocolla.

Bulk-Ore Chemistry

The concentration of carrier minerals of gold (Au), copper (Cu), silver (Ag), lead (Pb), zinc (Zn), arsen (As), stibnium (Sb), and mercury (Hg) by geochemistry analysis from FA/AAS (Table 1.). The concentration of gold in vein ranging from < 0.0002 ppm to 18.400 ppm. The highest concentration is found in third generation veins which are laminated quartz±calcite in argillic alteration. To show the correlation between two ore-carrier minerals, a linear function logarithmic graph was generated (Fig. 7.).

Those sulfides could be pathfinder minerals for the exploration of the metamorphic-hosted gold deposit. In general, gold is very fine-grain, but occasionally native gold is visible in quartz veins. Bulk-ore chemistry analyzed by FA/AS (Fire Assay/Atomic Absorption Spectrometry) indicates a very broad and erratic variation of gold grade ranging from below detection limit <0.0002 ppm to 18.4000 ppm Au (Table 1). Based on linear function logarithmic graph (Fig. 8) between gold

(Au) and Arsen (As), Au to stibnium (Sb), and Au to mercury (Hg) show linear graphics, so that Sb, As, and Hg can be seen as pathfinders to find the occurence of gold (Au) in study area. However, Au and other elements do not show any linear graphic. This indicates that the elements can not be seen as path finders in determining gold occurence in the study area.

However the relation of arsen (As) to stibnium (Sb), Sb to mercury (Hg), and As to Hg, also show the presence of linear graphic. This indicates that As can be seen as path finder to find Sb and Hg. The same thing happens to Sb, it can be used as a path finder to find Hg and As.

Based on Linear function logarithmic graph which is characterized by the linear correlation between Sb and Hg, then it can be concluded that the deposits in study area is orogenic gold deposits and if correlated to the concept of orogenic gold deposits by Gebre-Mariam, et al (1995) due to the formation zone of orogenic gold deposits, then it is possible that the zone is in epizonal and mesozonal zone.

Table 1. Ore geochemistry of metamorphic-hosted gold quartz veins/reefs from Rumbia mountains, Bombana (in ppm).

Samples code	Elements (ppm)							
	Au	Ag	As	Cu	Hg	Pb	Sb	Zn
DHR 11	0.0007	1.170	0.69	17.15	0.007	29.9	3.86	45.2
DHR 15	0.0007	0.232	2.53	45.1	0.021	8.22	0.975	56.1
DHR 16	<0.0002	1.620	4.22	71.8	<0.004	29.3	7.33	66.8
DHR 20	<0.0002	0.138	3.85	31.7	0.072	13.20	0.675	47.1
DHR 24	0.0004	1.420	5.38	28.1	0.013	48.2	6.85	87.9
DHR 25	0.0008	0.161	5.35	13.75	0.005	8.18	1.285	12.7
DHR 34	0.0048	0.619	27.8	123.5	0.015	24.4	2.46	34.7
DHR 35A	0.0779	0.093	194.5	7.70	0.577	4.22	19.60	4.3
DHR 50	0.0017	0.650	1810	43.0	1.375	83.0	6170	109.5
DHR 55	0.0124	0.014	49.1	61.9	0.287	11.15	1.795	59.5
DHR 62	0.0049	0.405	17.50	7.79	0.065	11.40	28.0	12.3
DHR 66	0.0071	0.191	160	708	0.085	10.10	3.21	138.5
DHR 74B	0.0009	0.491	2.52	4.70	0.010	19.45	5.06	10.8
DHR 76A	0.0009	0.103	3.23	17.70	0.076	19.35	0.733	48.4
DHR 81A	0.0014	0.564	32.4	179.0	0.014	9.10	2.06	61.3
DHR 85A	0.0024	3.10	2.44	1505	0.020	3.99	0.739	59.4
DHR 87	0.0002	0.281	2.88	1150	0.010	8.44	6.30	11.8
DHR 87A	0.0015	0.112	4.11	30.8	0.032	24.4	0.635	27.9
DHR 97A	<0.0002	0.041	4.48	51.00	0.011	4.68	1.835	39.9
DHR 101	0.7200	0.300	1840.0	43.00	0.080	6.00	21.000	53.0
DHR 103	0.0800	0.100	69.00	26.00	0.210	2.00	2.000	14.0
DHR 104	18.4000	0.300	192.00	44.00	0.310	27.00	62.000	52.0
DHR 105	0.9800	< 0.100	292.00	23.00	0.150	28.00	17.000	49.0
DHR 107	3.7600	0.100	852.00	25.00	0.340	11.00	37.000	42.0
DHR 108	0.2600	0.100	201.00	44.00	0.440	9.00	148.000	57.0
DHR 109	0.6300	< 0.100	118.00	28.00	0.070	9.00	32.000	53.0
DHR 110	0.1500	0.300	279.00	43.00	0.290	18.00	160.000	77.0
DHR 111	0.2200	0.100	75.00	45.00	0.080	11.00	34.000	20.0
DHR 113	< 0.0100	0.100	18.00	15.00	0.430	< 2.00	7.000	11.0

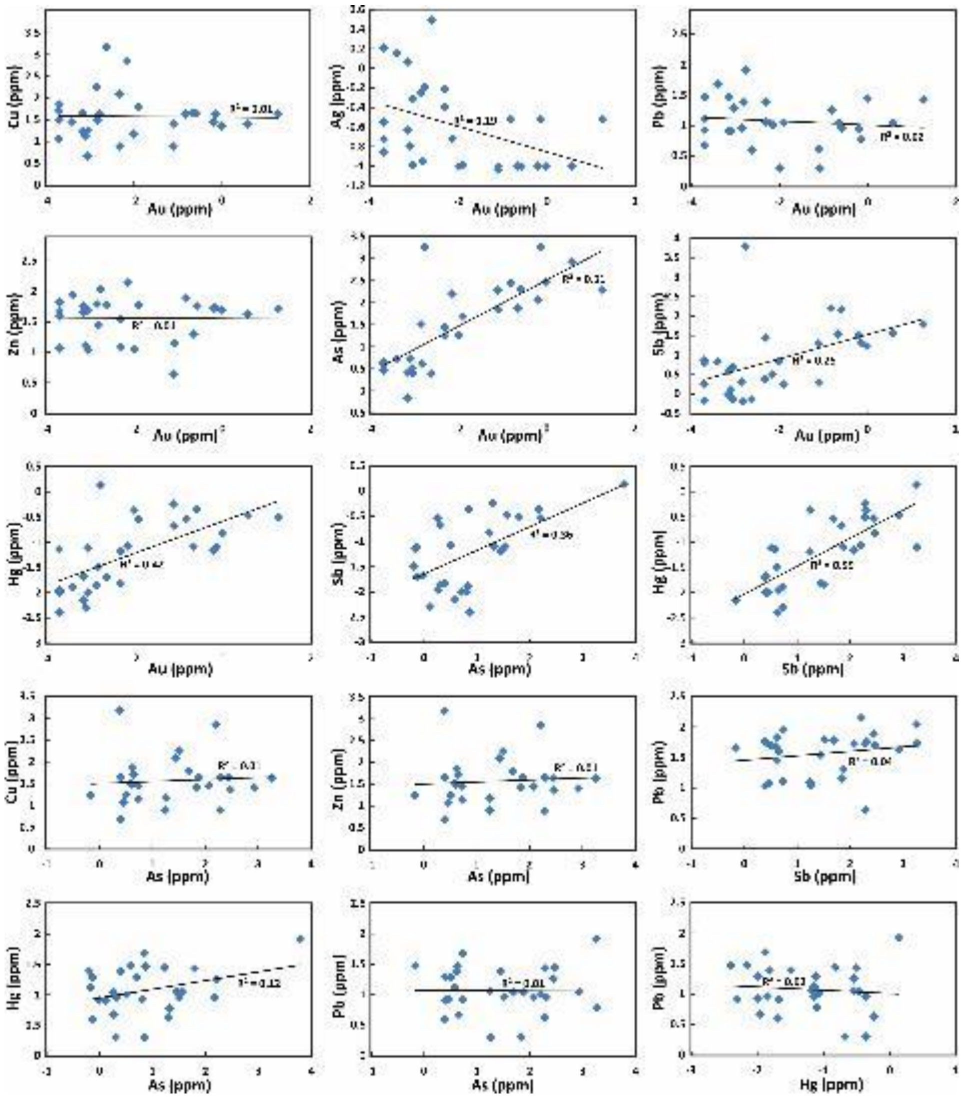

Fig. 8. Linear function logarithmic graph showing the correlation between Au to Cu, Ag, Pb, Zn, As, Sb, and Hg; and the correlation between As to Sb, Sb to Hg, As to Cu, As to Zn, Sb to Pb, As to Hg, As to Pb, and Hg to Pb.

8. Conclusion

Hydrothermal alteration of gold deposits consists of three zones such as sericitic, argillic, propylitic alterations. The quartz veins consist of 3 (three) types of veins such as quartz vein lied parallel to the foliation, quartz veins which crosscuts the first generation of veins/foliations and the laminated quartz vein which is the gold bearing quartz vein. As for how the characteristics of quartz vein which associated with the ore minerals, the quartz vein texture is generally deformed, segmented, laminated, massive, brittle, and sometimes sigmoidal.

The gold-bearing-quartz vein is commonly found in metamorphic rocks such as mica schist, chlorite schist, and phyllite which are petrologically categorized into facies of greenschist, where this type of metamorphic facies mostly become the host of orogenic gold deposits in the entire world.

The veins contain erratic gold in various grades from below detection limit <0.0002 ppm to 18,400 ppm. Mineralogically, gold is genetically related to consist of pyrite (FeS_2), chalcopyrite ($CuFeS_2$), hematite (Fe_2O_3), cinnabar (HgS), stibnite (Sb_2S_3) and goethite ($FeHO_2$). It shows that the element of stibium, arsenic and mercury can be used as a pathfinder (reference) to find the existence of gold.

Gold is mainly identified in the form of 'free gold' among silicate minerals particularly quartz. Based on characteristics hydrothermal alteration, quartz vein, host rock and mineralogically, it obviously indicates that the primary gold deposit present in the study area is of orogenic gold deposit type . The orogenic gold deposit is one of the new targets for exploration in Indonesia.

Acknowledgments

This paper is a section of the first author's PhD thesis completed at the Department of Geological Engineering, Faculty of Engineering, Gadjah Mada University Yogyakarta, Indonesia. This study was made possible through financial support from Ristekdikti. The authors are very thankful to the management of the Panca Logam Makmur (PLM)

Company, which has given permission to do. Thanks to Mr. La Ode Ngkoimani and Suryawan Asfar for facility assistance during field fieldwork. Special thanks to my students from the Department of Geological Engineering, Halu Oleo University for their assistance during the fieldwork. We also would like to thank the Head and staff of the Geological Engineering Department, Faculty of Engineering, Gadjah Mada University who gave me permission to access to the laboratories.

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