MINERALOGY AND ORIGIN OF COPPER-GOLD BEARING SKARN WITHIN THE BATU HIJAU PORPHYRY DEPOSIT, SUMBAWA ISLAND, INDONESIA

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Abstract

The aim of this study is to emphasize on the origin of copper-gold bearing skarn mineralization at the Batu Hijau deposit which is located at the southwestern corner of Sumbawa Island, Indonesia. Although most skarn are derived from limestones, nolimestone is known in the Batu Hijau deposit. Ca-rich andesitic volcaniclastic host rocks favor skarn alteration within the Batu Hijau deposit. The type of skarn can be classified as calcic-exoskarn, and locally controlled by faults and fractures. Two major stages consisting of four sub-stages of skarn forming processes can be divided by the mineral assemblages of skarn as prograde and retrograde stages. The prograde skarn consists of clinopyroxene and garnet ± magnetite formed at the trapping temperature of 440°-480 °C with 34-38 wt% NaCl eq. while retrograde skarn alteration is dominated by Fe-rich minerals such as amphibole and epidote formed at the trapping temperature down to 340°-360°C with 4-8 wt% NaCl eq. Opaque minerals include chalcopyrite, pyrite, sphalertite, and minor galena and bismuth- telluride. Gold was precipitated in the retrograde stage associated with bismuth-telluride minerals. The sulfur isotope data of skarn ranges from +0.1 to +1.7‰ (sulfide), and porphyry systems range from 0.04 to1.4‰ and 10‰ to 15‰ (sulfide and sulfate respectively). According to the fluid inclusion and sulfur isotope data, the origin of skarn and porphyry system can be suggested to be that the magmatic origin. Furthermore, the sulfur isotope data of the deposit evidently shows that a porphyry- related skarn mineralization exhibiting transition from one style to the next can be relatively rapid. The result of this research has indicated that the range of porphyry-related deposits, skarn and porphyry systems can form during a single prolonged hydrothermal event.

Keywords: Batu Hijau deposit, Copper-gold bearing skarn, Fluid inclusion, Indonesia, Magmatic origin, Sulfur isotope

Introduction

A copper-gold bearing skarn was newly found in the deep level of the Batu Hijau deposit which is an island arc porphyry deposit, located in the southwestern corner of Sumbawa Island, in the west Nusa Tenggara Province, Sunda-Banda Archipelago of Indonesia. In this paper, the mineralogical and geochemical data on skarn, fluid inclusion thermometry, and sulfur isotope composition of skarn ore were investigated in order to understand the process of skarn formation. Sumbawa lies along the tectonically active east-west trending Sunda-Banda magmatic arc that is a product of the convergence of three major tectonic plates: the Indian-Australian, the Eurasian and the Pacific Plates.

Figure 1. Map of Indonesia and surrounding areas showing the location of Batu Hijau deposit (modified from Carlile and Mitchell, (1994)).

Deposit Geology

More than 98% of Indonesian gold and copper resources are derived exclusively from six major Neogene mineralized magmatic arcs which include Sunda-Banda, Aceh, Central Kalimantan, Sulawesi-East Mindanao, Halmahera and Medial Irian Jaya (Central Range-Paouon fold and thrust belt) (Carlile and Mitchell, 1994). The Batu Hijau porphyry Cu-Au deposit is located in the southwestern corner of Sumbawa Island, in the west Nusa Tenggara Province, Indonesia. Sumbawa lies along the tectonically active east-west trending Sunda-Banda magmatic arc that is a product of the convergence of three major tectonic plates: the Indian-Australian, the Eurasian and the Pacific Plates (Hamilton, 1979).

The Batu Hijau deposit is dominantly underlain by andesitic volcaniclastic rocks (Early to Middle Miocene). A premineralization porphyritic quartz diorite was intruded by equigranular quartz diorite and tonalite porphyries (Clode et al., 1999). Detailed mapping within the Batu Hijau deposit identified five major structural trends: N-S, E-W, NE-SW, NW-SE and radial pattern (Priowarsono and Maryono, 2002). The most common two major structures; the northeasterly trending Bambu- Santong fault zone and northwesterly trending Katala-Tongoloka Puna fault zone transect the Batu Hijau district at the Santong diatreme, 2 km NW of the Batu Hijau deposit. Figure 2 shows the geology of the deposit illustrating the borehole sample location, and Figure 3 shows the lithology distribution along cross-section (A) and the 3D schematic diagram showing the skarn distribution at deeper levels around the intermediate tonalite porphyry intrusion (B).

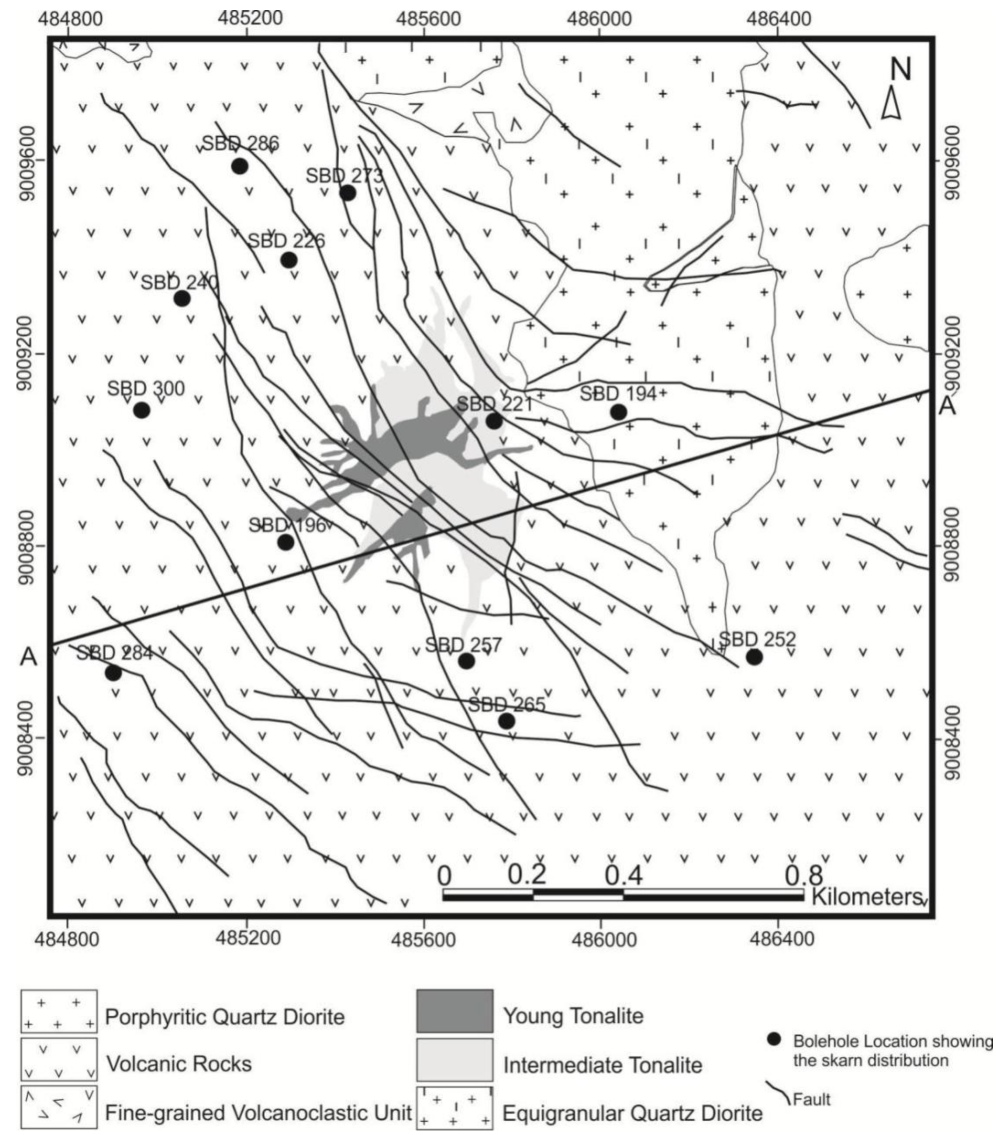


Figure 2. Geological map Batu Hijau deposit. Black circles show the location of the boreholes and location of skarn mineralization (modified from Newmont, (2008)

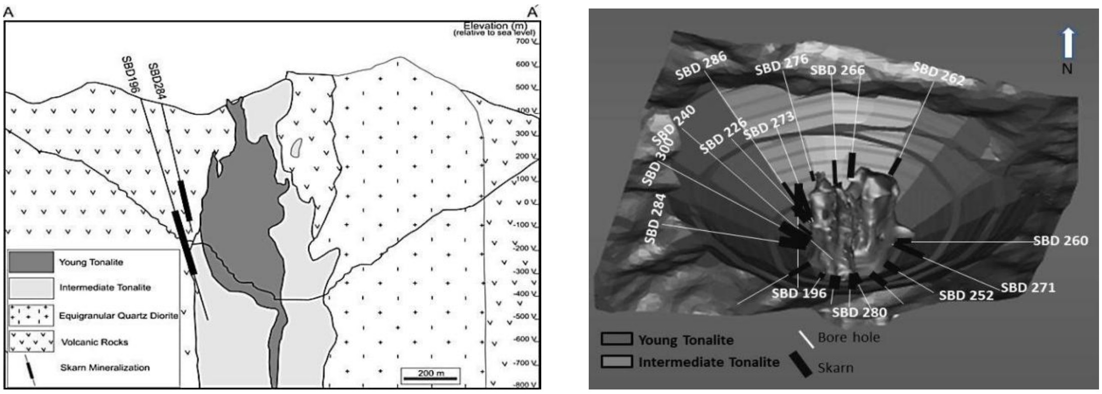


Figure 3. (A) Lithologic distribution of the cross-section (Section 070) along A-A' in Figure 2 and the vertical profile of the borehole SBD-196 and SBD-284, (B) 3D schematic diagram showing the skarn distribution at deeper levels around the intermediate tonalite porphyry intrusion (modified from Newmont, (2008)).

Occurrences of Skarn Zonation and Ore Mineralization

The skarn and ore mineralization is developed as a result of metasomatic reaction between the calcium-rich andesitic volcaniclastic rocks and intermediate tonalite porphyry intrusions at deeper levels (Figure 3). Skarn and related ore mineralization are extensively faulted caused by the geology in the Batu Hijau deposit and which is complicated in structure.

Whereas most skarn deposits are derived from limestone or carbonate rocks (Einaudi et al, 1982), copper-gold bearing skarn at the Batu Hijau deposit clearly defines skarn occurrences that resulted from the complete replacement of Ca-rich volcaniclastic units and with no evidence of limestone in the Batu Hijau deposit (Idrus et al, 2009). The skarn in Batu Hijau is typified by banded structures and characterized by anhydrous and hydrous calc-silicate minerals (garnet, diopside, amphibole, epidote), chlorite, quartz, clay minerals, sulfides (pyrite, chalcopyrite, sphalerite, galena, bornite), oxides (magnetite, hematite) and carbonates (calcite) developed along the contact between intermediate tonalite porphyry stock and the volcanic host rocks.

Mineralogy

Skarn Minerals and Associated Ores

Andraditic garnet and diopsidic clinopyroxene are the dominant skarn minerals in the Batu Hijau deposit. Most garnets are coarsed-grained, massive and brecciated in nature associated with magnetite. Under the microscope, garnet is euhedral and exhibits zoning. Aggregates of coarse- grained garnets are commonly observed while fine-grained garnet and occasional crystals of feldspar are often filled within the calcite matix (Figure 4a). Most garnet shows distinct concentric zoning (Figure 4b). Veins and veinlets of magnetite cut across the clinopyroxene (Figure 4c). Under the microscope, euhedral clinopyroxene coexists with a lesser amount of quartz, sphene, and hematite. Epidote- bearing skarn replaced garnet and is widely distributed. Microscopic observation reveals that epidote is anhedral when it is associated with garnet, implying a late formation after garnet (Figure 4d). Moreover, it is also commonly associated with magnetite and minor sericite, sphene and quartz. Magnetite occurs both as massive and brecciated varieties. Most ores are composed of magnetite associated with chlorite, calcite and quartz, filling fractures or spaces. High grade ores are found in the broken magnetite zone. Ore minerals include chalcopyrite, pyrite, sphalerite; galena associated with gold and bismuth-telluride fills the cracks and cavities within the magnetite-rich zone.

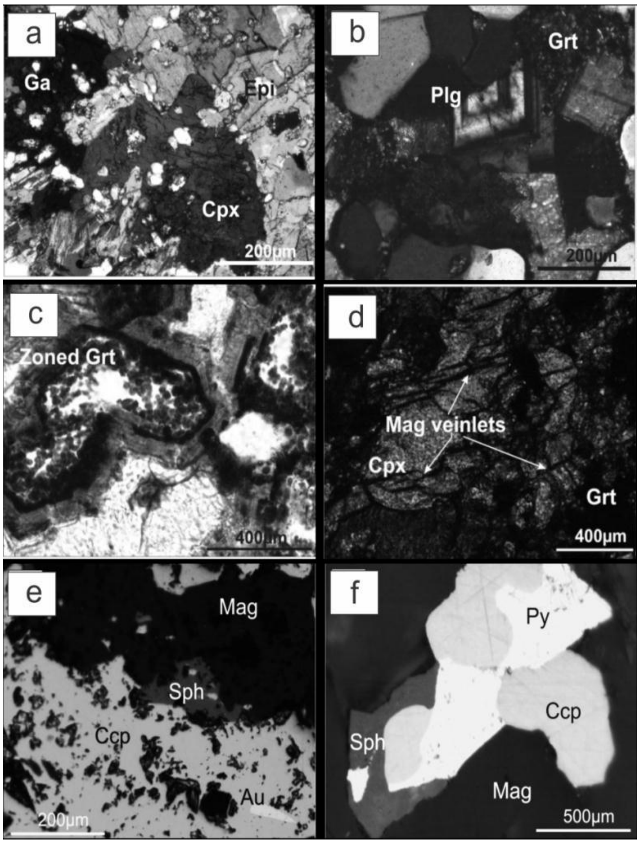


Figure 4. Photomicrograph of representative samples from the Batu Hijau drill hole showing skarn and ore mineral assemblages. (a) epidote (Epi) showing granoblastic texture and replace garnet associated clinopyroxene (Cpx); (b) zoned plagioclase associated with replacement of clinopyroxene (Cpx) by chlorite (Chl); (c) garnet (Grt) shows concentric zoning; (d) magnetite (Mag) veinlets cut cross clinopyroxene (Cpx); - Polished thin section under reflected light, (e) blebs of native gold in chalcopyrite (Ccp) associated with sphalerite (Sp) and magnetite (Mag) and (f) replacement of pyrite (Py) by chalcopyrite (Ccp) associated with sphalerite (Sph).

Paragenesis

Paragenetic sequence of skarn at the Batu Hijau deposit appears similar to other skarns (Einaudi et al., 1982; Newberry, 1987; Meinert, 1993; Kwak, and White, 1982). Mineralogical and textural evidence suggest that the process of skarn formation can be categorized into two discrete stages of prograde and retrograde events which consist of four sub-stages. The early prograde stage is hornfelsic skarn characterized by fine-grained garnet and clinopyroxene. The early retrograde stage is typified by precipitation of a large amount of magnetite whereas epidote and a small amount of quartz precipitated simultaneously with magnetite. Sulfide minerals such as chalcopyrite, pyrite, sphalerite, galena associated with gold and bismuth-telluride and hydrous minerals precipitated during this stage. The generalized paragenetic sequence of formation of the skarn and ore minerals from the Batu Hijau deposit is shown in Figure 5.

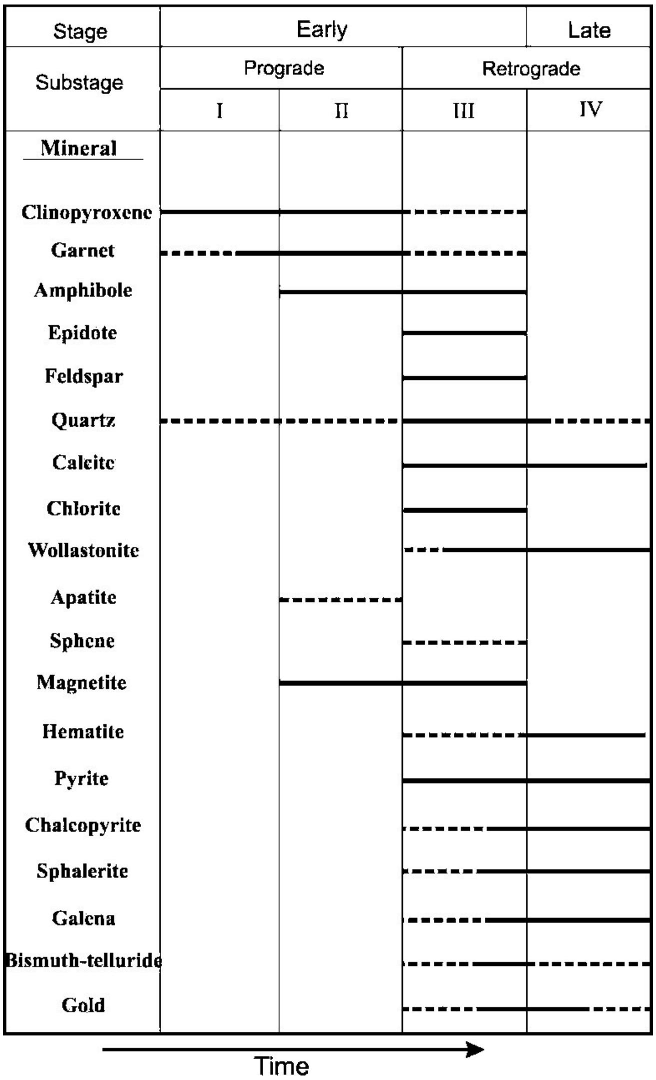


Figure 5 Paragenetic diagram for skarn and ore minerals at the Batu Hijau deposit

Fluid Inclusion Study

Analytical Procedures

Fluid inclusions were examined in six samples from quartz veins/veinlets associated with prograde and retrograde skarn minerals in order to estimate the spatial and temporal variations of temperatures and the composition of the hydrothermal fluid. The homogenization and the ice melting temperatures of fluid inclusions were obtained on double polished thin sections using a Linkam THMS-600 stage and also a USGS-adopted Fluid Inclusion heating/freezing stage. The melting temperatures of several metals and the ice melting temperatures of NaCl solutions of known concentration were measured in order to confirm the accuracy of the stage.

Results

Fluid inclusions from the quartz sample associated with prograde and retrograde stages vary in size from 10-50 µm. The type of fluid inclusion follows the classification by Nash (1976), as follows: Liquid-rich and vapor-rich two-phase inclusions mainly occur in the quartz associated with the retrograde stage and polyphase inclusions containing a daughter mineral are found mainly in quartz associated prograde minerals (Figure 6). Fluid inclusions in the prograde stage homogenized over a broad range, from 340ºC to 515ºC with a salinity between 24 and 48 wt% NaCl eq. whereas fluid inclusions in the retrograde stage are homogenized between 200ºC and 396ºC with the salinity between 1 and 10wt% NaCl eq. (Figures 7 & 8). However, the trapping temperature ranges from 440°- 460°C for the prograde stage and 340°-360°C for the retrograde stage. The high temperature and high-salinity fluid in skarn is usually interpreted to represent a magmatic fluid (Burnham, 1979). Table 2 shows the summary of the fluid inclusion data.

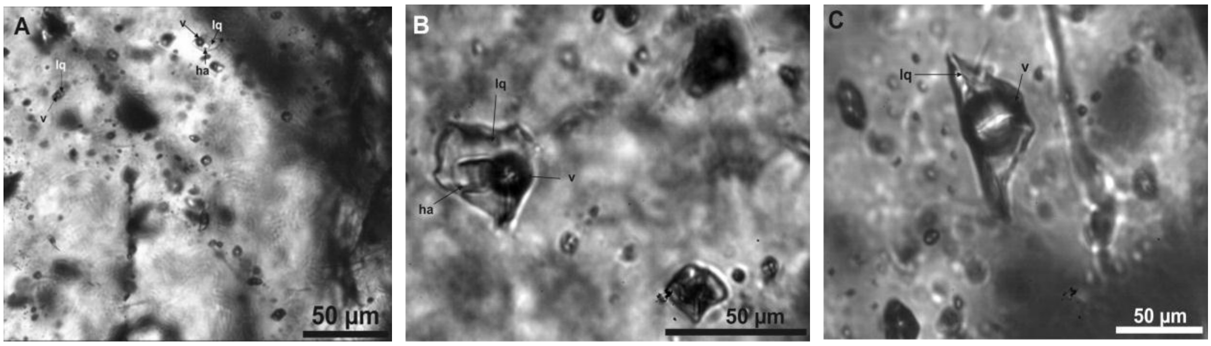


Figure 6 Photomicrographs of morphology and various types of fluid inclusion from skarn minerals at the Batu Hijau deposit.

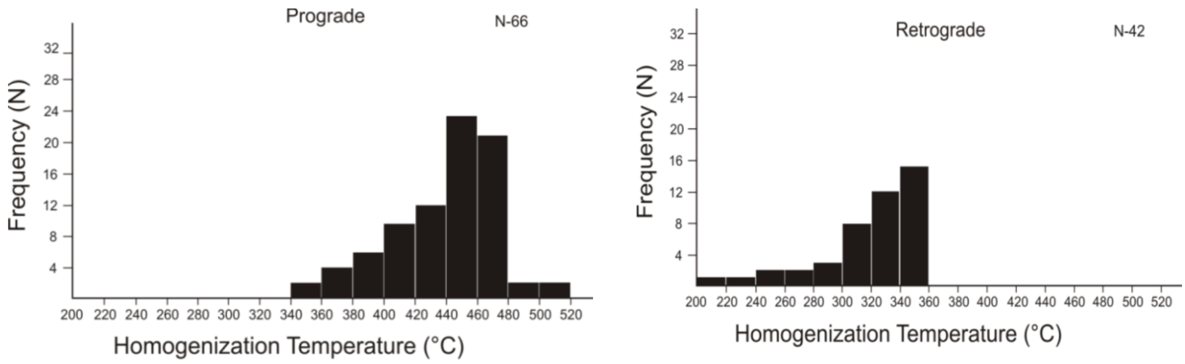


Figure 7 Frequency distribution diagrams of homogenization temperature (Th) of fluid inclusions in quartz associated prograde and retrograde stages.

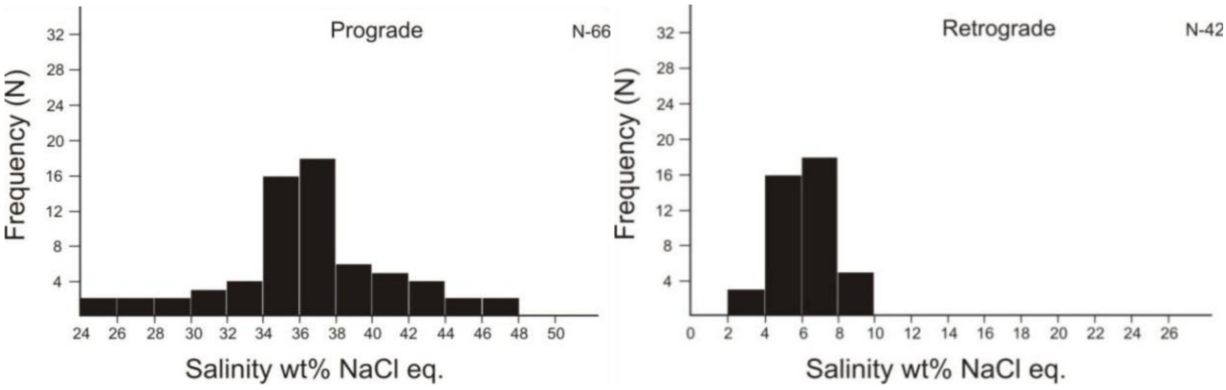


Figure 8 Frequency distribution diagrams of salinity (wt% NaCl eqn.) of fluid inclusions in quartz from prograde and retrograde stages.

Table 2 Summary of Fluid Inclusion Microthermometry of Skarn Mineralization from the Batu Hijau Deposit

Sample No.	**Depth (m)**	**N**	**Host**	**Origin**	**Size (µm)**	**Phase**		**Salinity wt% NaCl eq.**	**h**	**Trap ping**	**Stage**
226	694	21	Qtz	P	5-30	L+V+h	156-273	29-36	257-510	251-470	Prograde
252	1031	14	Qtz	P	5-30	L+V+h	233-416	30-48	340-562	330-515	Prograde
286	710	12	Qtz	P	10-30	L+V+h	243-263	30-39	380-504	362-467	Prograde
	814	19	Qtz	P	5-33	L+V+h	159-288	30-37	320-511	308-473	Prograde
273	930	22	Qtz	P	10-30	L+V	(-1.9)-(-3.6)	3-10	262-404	255-382	Retrograde
284	997	20	Qtz	P	10-50	L+V	(-1.6)-(-6.3)	3-6	246-420	200-396	Retrograde

Abbreviation: Tm: temperature of melting (ice), Th: vapor-liquid homogenization temperature, Td: dissolution temperature of halite, Qtz: quartz, N: number of measurements

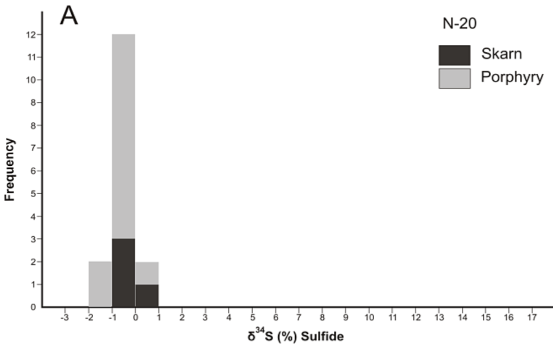
Sulfur Isotope Study

Analytical Procedures

The sulfide mineral grains from skarn were hand-picked from a specimen under a binocular microscope. The sulfur isotope analysis for the sulfides from the skarn was performed at the Activation Laboratories Ltd. Ontario, Canada. Additionally, sulfide and sulfate minerals (pyrite, chalcopyrite, bornite, gypsum and anhydrite) from twelve samples of vein type deposit of porphyry at the Batu Hijau deposit (Data analyzed by Imai and Nagai, 2009) (unpublished data) were previously determined at the Department of Earth and Planetary Sciences, University of Tokyo by Dr. Dana Anton using a Thermo Finnigan delta plus mass spectrometer for SO_2 gas prepared by the procedure described by Yanagisawa and Sakai (1983).

Results

The δ34S value (sulfide) from the Batu Hijau skarn ranges from +0.1 to +1.7‰, and sulfide and sulfate values from porphyry systems range -0.04 to1.4‰ and 10‰ to 15‰ respectively. The δ34S values for sulfides fall in the narrow range -3 to +1 per mil close to the accepted mantle range (Ohmoto and Rye, 1979). Histogram of δ34S values from the sulfides and sulfate are shown in Figure 9 and Table 3 showing the summary of sulfur isotope data.



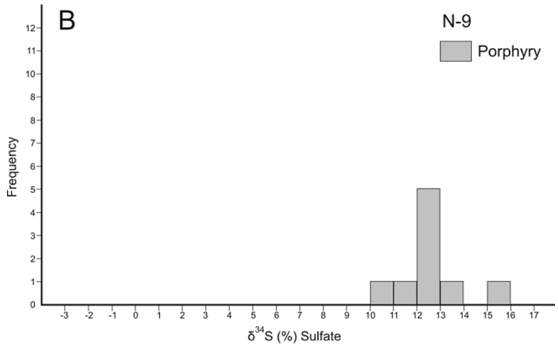


Figure 9 Histogram of δ34S values from sulfur. A. Sulfide values from skarn and porphyry mineralization and B. Sulfate value from porphyry with reference to the mineral sample type.

Table 3 Summary of Sulfur Isotopic Composition of Sulfide and Sulfate from Skarn and Porphyry within the Batu Hijau Deposit

Sample no.	Depth (-m)	Elevation	Mineral	Locality, Type	δ^{34}S(%)
SBD-240	734	450.3	py	skarn	1.7
SBD-286	776	322.7	py+cp	skarn	0.1
	907		py+cp	skarn	0.2
	969		py	skarn	1
SBD-021	285.4	220	bn+cp	porphyry	-0.1
	441.7		bn+cp	porphyry	0.4
SBD-183	461.2	460.5	bn+cp	porphyry	0.1
	722		py	porphyry	0.6
	792		bn+cp	porphyry	-0.9
	957.9		cp+py	porphyry	0.3
SBD-194	155.4	405	cp	porphyry	0.2
	891		cp+py	porphyry	0.6
SBD-221	186.5	250	bn+cp	porphyry	0.4
SBD-257	1263.2	-320	py	porphyry	1.4
	1263.2		anh	porphyry	15.8
	1292		gyp	porphyry	12.6
	1294.2		py	porphyry	0.7
	1294.2		anh	porphyry	12.9
	1322.5		anh	porphyry	12.9
	1428.2		py	porphyry	0.7

	1472.9		py	porphyry	0.8
	1472.9		anh	porphyry	13.5
	1484.3		gyp	porphyry	11.9
	1541.7		py	porphyry	0.5
	1541.7		gyp	porphyry	12.3
	1579.5		py	porphyry	1.3
	1579.5		anh	porphyry	10.9
SBD-265	1327.8	340	py	porphyry	0.8
	1327.8		anh	porphyry	12.1

Abbreviation: anh: anhydrite (sulfate), bn: bornite (sulfide), Cp: chalcopyrite (sulfide), py: pyrite (sulfide), gyp: gypsum (sulfate)

Discussion

The compositions of Batu Hijau skarn minerals indicate an oxidizing environment of deposition. The clinopyroxene (diopside) co-exists with or is replaced by andradite which suggests that clinopyroxene and andradite are formed in an oxidized environment (Kwak and White, 1982; Meinert, 2000). In addition, the common occurrence of magnetite associated with chalcopyrite and pyrite supports the conclusion of an oxidizing environment during skarn formation.

The paragenesis of skarn evolution from the Batu Hijau deposit shows two main stages consisting of four sub-stages. Sub-stages I and II mineral assemblages are dominated by clinopyroxene and garnet. These two stages are considered to represent prograde anhydrous skarn development, whereas stage III, which is dominated by hydrous minerals (amphibole, epidote, chlorite), and stage IV, which comprises of hematite and calcite, are considered to represent retrograde hydrous skarn development. Small blebs of gold occur as inclusions in chalcopyrite associated with sphalerite.

According to the fluid inclusion data, the high temperature of prograde stage up to 515°C (trapping temperature of 440°-480 °C) and the salinity of 48 wt% NaCl eq. correspond to a fluid pressure of ~400 bars and lithostatic depth of ~1.5 km (hydrostatic depth of 4 km). For the retrograde stage, temperature up to 396°C (trapping of 340°-360°C) corresponds to a fluid pressure of ~180 bars which is equivalent to a lithostatic depth of 0.8 km (hydrostatic depth of 1.8 km). The high-temperature and high-salinity fluid in skarn is usually interpreted to represent an orthomagmatic fluid (Burnham, 1979) as it is interpreted at the Mid-Patapedia prospect (Williams-Jones and Ferreira, 1989) and Mines Gaspe (Shelton, 1983).

In addition, the $\delta^{34}S$ values for sulfides fall in the narrow range -3 to +1 per mil close to the accepted mantle range and porphyry copper deposits are the most likely candidate for magmatic, igneous source of sulfur (Ohmoto and Rey, 1979). It can either be explained by magmatic–hydrothermal processes, or by incorporation of an external, isotopically light, sulfur source such as biogenic sulfide, which is characteristically depleted in $\delta^{34}S$. In this paper, sulfur isotope data range from -3 to +1 per mil. It can be suggested that the source of Batu Hijau deposit is of magmatic origin. Figure 11 illustrates the $\delta^{34}S$ values for sulfur-bearing minerals in hydrothermal deposits showing the Batu Hijau deposit (Ohmoto and Rye, 1979).

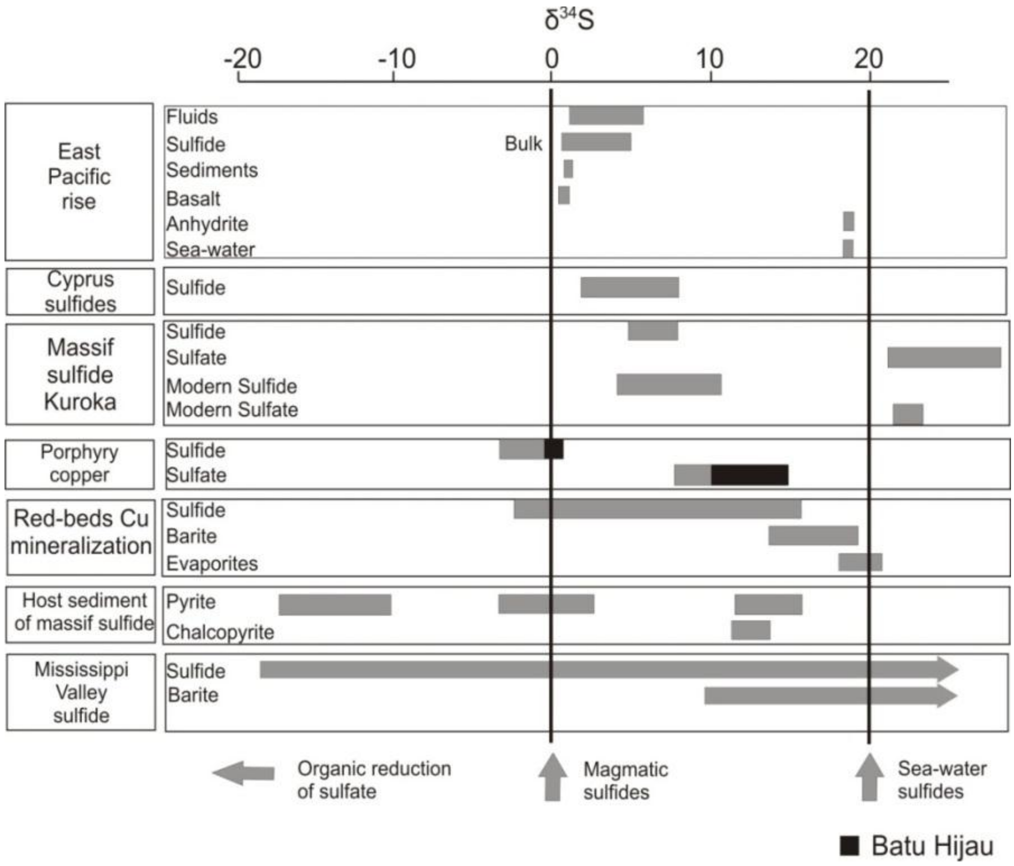


Figure 11 he $\delta^{34}S$ values for sulfur-bearing minerals in hydrothermal deposits (modified from Ohmoto and Rye, 1979).

The genetic development of skarn in the Batu Hijau deposit documents that a hornfelsic skarn was first formed in response to the intrusions into Ca-rich layer of host rocks, which converted the volcanic rocks as into the prograde isochemical skarn. The skarn development is controlled predominantly by temperature, pressure, composition and texture of the host rock. Subsequently, the skarn system was later influenced by the presence of calcium-rich host rock to produce massive amount of calc- silicates (garnet and pyroxene skarn) as prograde skarn (metasomatic stage). The mineralogy formed during the prograde stage is characteristically coarser-grained. Sulfide and oxide deposition commences during the latter stage of metasomatic skarn development. Magnetite dominates over sulfides forming either by replacement of garnet or pyroxene at the tonalite intrusive contact. This stage is characterized by the replacement of earlier prograde anhydrous minerals by late stage hydrous minerals. The retrograde skarn is composed of complex mineral assemblages of many phases which are the main stage of sulfide and oxide formation in skarn. Sulfide mineralization and retrograde alteration in skarn system is typically structurally-controlled and cuts across the prograde skarn due to its brecciated nature.

Conclusions

The copper-gold bearing skarn within the Batu Hijau deposit is a unique style of skarn mineralization as hosted by Ca-rich andesitic volcanic rocks. It is a calcic exo-skarn. The Ca-rich volcanic rocks favor metasomatic alteration to form the skarn within the

Batu Hijau deposit. The skarn system is characterized by a Fe-rich and oxidized paragenetic sequence as an early hornfels stage, a massive prograde skarn replacement, and a somewhat restricted retrograde alteration. Gold mineralization occurs closely associated with sulfide minerals of the late epidote and/or amphibole by the retrograde alteration of pyroxene-bearing zones, or magnetite-rich shear zone. Fluid inclusion analysis and sulfur isotope study showed that skarn and porphyry were from a similar source, and the origin of the mineralization is predominantly a magmatic sulfur source, hydrothermal magmatic origin. The Batu Hijau deposit holds evidence that the porphyry-related skarn deposits are mineralogically zoned and that transition from one style to the next can be relatively rapid.

Acknowledgments

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