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Zonality of Gold Ore and Prospects of Gold-Quartz-Sulfur in Khauau Deposit, Binhvan Commune, Chomoi District, Backan Province, Vietnam

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Abstract – Khauau gold deposit, Binhvan commune, Chomoi District, Backan Province, Vietnam, is located in the Dong Bac Bo intracontinental orogenic belt. This is one of the important gold mineralization areas of Vietnam. To study the zonation of mineralization and to predict the prospect of deeply hidden buried gold ore, a research was conducted based on mineral facies analysis, fluid inclusion thermometry, ICP-MS chemistry, and morphological orebody size. The results indicate that the gold mineralization is derived from medium to medium–low temperature hydrothermal fluids associated with deep-seated formations. Inclusion homogenization temperature is from 170 to 310^{o} C, and the main ore mineral components include pyrite, arsenopyrite to a lesser extent galena, sphalerite, and chalcopyrite. Gold mineralization-quartz-sulfur Khauau deposit is divided into three zones, which from the top to the bottom is as follows: ore zone 1 is gold-quartz-pyrite poor sulfur; ore zone 2 is gold-quartz-polymetallic; ore zone 3:is gold-quartz-arsenopyrite and pyrrhotite. Ore bodies are likely located at the depths of 125 to 540 m with many extending beyond 400 m. The depth of ore-forming processes is 562 m and the zoning coefficient of Kz= 0.83. Accordingly, it is possible to predict the prospect of the Khauau gold deposit, Binhvan commune, Chomoi District, Backan Province, to a depth of more than 500 m, and possibly extend to depths of up to 5 km.

Keywords: gold ore-quartz-sulfur, ore zone, zonation, polymetallic sulfur

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Introduction

Background

Primary gold deposit in Vietnam and around the world is of interest to many geologists (Binh, 1994, 1997, 2010; Can, 1994; Canh, 2000; Orekhov, 2015; Zaitsev, 2018; Pavel *et al.,* 2020; Tuan *et al.,* 2023). Khauau gold deposit is located in the Boc-Backan anticlinorium, in the southeastern part of the Dong Dong Bac orogenic belt (Figure 1b). Petrotectonic assemblage main Cambria-Silurian aulacogen type (Tri *et al.,* 2016; Hoa, 2010). Khauau gold deposit has the coordinates of 21°52' - 21°54' north latitude and 105°54' - 105°57' east longitude, and has an area of approximately 15 km^2 (Figure 1a).

Research on zonation, erosion rate, and the preservation ability of ore mineralization has been of interest to geologists (Zhai, 1999; Zhai *et al.,* 2000). To determine the zoning, the depth, and the

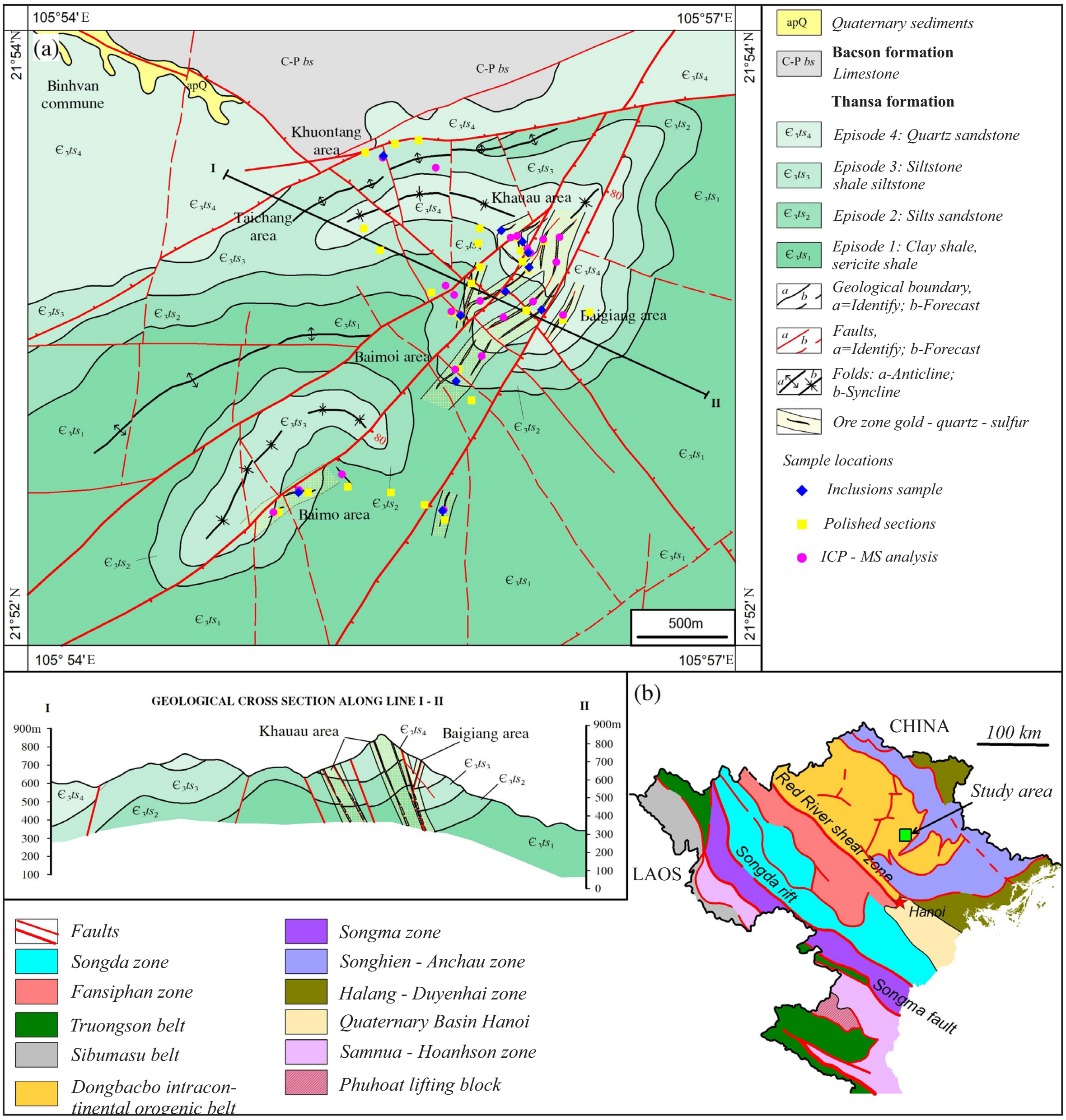

Figure 1. (a) Geological structure and mineral diagram of Khauau area mine (Dat *et al.,* 2020), and (b) Diagram of tectonics locations in northern Vietnam and the studied area (Tri, 2009).

erosion rate of geological formations, including deep hidden ore bodies (Li *et al*., 2006; Liu and Ma, 2007; Hung *et al.,* 2023) the geochemical anomalies were analyzed associated with mineral exploration. The basis for the research on zoning, erosion rate, and conservation capacity of mineralization is as follows:

The first is based on mineral characteristics, ore-forming processes, mineral assemblage, and geochemical variability properties of hydrothermal mineral deposits.

The second is based on the formation temperature, according to the correlation between temperature and of ore forming depth to divide into crystalline mineralization stages.

The third is based on elemental geochemical characteristics, the correlation of ore-forming elemental with ore-forming depth.

In addition, it also relies on the characteristics of hydrothermal transformation, petrotectonic assemblage, and the rules of ore body distribution to evaluate the horizontal zonation.

Geological Settings

The studied area includes terrigenous deposits and metamorphism rocks of The Thansa Formation ($Є_3$ *ts*), accounted for about 90 % of the studied area. The main composition includes: the lower part which is sericite schist interwoven with shale, the upper part which is sandstone, quartz sandstone, and siltstone. The north of the mine zone is limestone of Bacson Formation (C-P*bs*), marmorization limestone, and thickly layered (Dat *et al.,* 2020; Tri and Khuc, 2009). The terrigenous rock deposits of The Thansa Formation serve as the primary host rocks for the ore. The gold ore is located in the Khauau syncline structure of Boc- Backan anticlinorium. The northeast − southwest fault system plays the role of ore control element, and the operation of this fault system creates broken rock zones, shear zones containing gold mineralization (Dat *et al.,* 2020; Long *et al.,* 2000; Khiem *et al.,* 1997) (Figure 1a). Hydrothermal transformation phenomena include silicification, sericitization, chloritization, berezitization, sulfurization, and carbonation.

This study was conducted with the aim to determine the characteristics of gold-quartz-sulfur ore zonation, to review the ore-forming depth, and the erosion depth characteristics.The research result helps evaluate the prospect hidden deeply buried ore body, and guide the search and exploration work.

Materials and Methods

Field investigations were conducted across all the studied areas at a scale of 1:10,000. Additionally, surveys were carried out along structural sections, with a higher density of survey points in regions with complex structures, signs of mineralization, and variations in petrological composition. At this stage, key issues such as regional geological structure characteristics, geological boundaries, and the relationship between mineralization and sampling were examined. In addition, during the survey, information about the length was also collected in the strike direction, ore outcrop height, vertical extent of ore-forming zones controlled by the mining tunnel systems and exploration boreholes.

The mineral facies analysis method was employed to examine mineral composition, structure, textures, ore relationships, ore-formation sequence, mineral assemblage, and ore-forming stages. Twenty-five gold ore samples were taken from the ore zones and ore bodies according to the survey lines and in order from the top to the bottom at different depth levels (Figure 1a). Mineral facies analysis was taken under an AXIOKOP 40 microscope at the Center for Geotechnology and Minerals, Vietnam Institute of Geosciences and Mineral Resources.

To determine the ore-forming temperature, the inclusion homogenization temperature analysis method was utilized. Ten inclusion samples were taken in quartz veins containing mineralization, associated with ore-forming processes. Samples were taken from the top to the bottom in the mining tunnels (Figure 1a). The sample was analyzed under an Linkam TMS 600 at the Center for Geotechnology and Minerals, Vietnam Institute of Geosciences and Mineral Resources.

To determine the content of rare earth elements, trace elements, and metals, the ICP-MS chemical analysis method was used. Twenty-three samples were taken in bedrock and hydrothermal alteration zones associated with ore bodies, across networks and survey lines (Figure 1a). The equipment used are: CARBOLITE furnace, SARTORIUS scale - BP 211 D (10-5g), and Agilent 7700x ICP-MS instrument. The analytical procedures are: TCCS 01/XH.2012; Limit: >10 ppb, at Radioactive-Rare Experimental Analysis Center, Geological League of Radioactive and Rare Elements, Vietnam Department of Geology.

The review of the ore-forming depth is as follows: research documents were used on the thickness, the development direction, and the slope direction depth of the ore bodies. Research process of hundreds of hydrothermal mines related to tungsten, fluorite, molibdenum, gold, copper, tin, and uranium in the world, Lir (1984) established the correlation coefficient (k) between the strike line length (l) and the slope direction depth (h) of hydrothermal ore bodies according to the formula (k= h/l) (Lir, 1984). Accordingly, Lir (1984) calculated the coefficient k= 0.6 for veined gold ore. This calculation have been applied to calculate the gold mineralization for Khauau gold deposit.

Assessment method of the denudation rate is one of the methods to evaluate the depth of distribution of gold ore bodies, and to calculate the vertical distribution of ore-forming elementals, from which to calculate the zoning coefficient of ore bodies according to the formula of Grigoryan and Beue (1977), namely:

$$Kz = \frac{Ag \times Pb \times Zn}{Cu \times Co \times Bi} \quad \text{................................(1)}$$

In which:
Kz is the denudation coefficient;
Ag, Pb, Zn, Cu, Co, Bi are elemental contents of Ag, Pb, Zn, Cu, Co, and Bi (ppm);
$Kz < 0.1$ under the ore-forming zone;
$0.1 \leq Kz \leq 10{,}000$ in the ore-forming zone;
$Kz > 10{,}000$ on the ore-forming zone.

Result

Characteristics of Ore Zonation

The Ore-Forming Stages

To study the zonation of ore, mineral assemblage (MA) was relied on. Each ore zone has a characteristic MS with different physical and chemical properties and conditions. Based on mineral facies analysis of gold mineralization-quartz-sulfur on the Khauau deposit (Table 1), three main ore-forming stages have been identified (Dat *et al.,* 2020) which are:

- Early ore-forming stage: MA are quartz-pyrite, arsenopyrite-gold. Ore mineral composition mainly includes arsenopyrite and pyrite with very little pyrrhotite. Hydrothermal alteration is characterized by silicification, berezitization, chloritization, and sericitization distributed at depth, in the areas of Baigiang, Baimo, Khauau, and Baimoi.
- Second ore-forming stage: MA are gold-quartz-polymetallic sulfur. Ore mineral composition mainly includes pyrite, chalcopyrite, sphalerite, with galena as a secondary mineral, arsenopyrite (Figure 2a). Hydrothermal alteration is characterized by silicification, chloritization, sericitization, berezitization. This is the main mineralization stage in the mine area distributed in Baigiang, Baimo areas, and deep parts of Khauau and Baimoi areas. Gold comes in small grained, widely disseminated form on a quartz base (Figure 2a).
- Third ore-forming stage: MA are gold-quartz-poor in sulfur, with the main ore mineral being pyrite, very little chalcopyrite, and sphalerite (Figure 2b). Hydrothermal alteration is characterized by silicification, chloritization, sericitization, berezitization, and sulfurization. This is the main ore-forming stage in the region, distributed in Khauau and Baimoi areas. Gold is in disseminated or small pocket-shaped form in sulfur minerals and in quartz veins, growing in the northeast –southwest direction.

Geochemical Anomaly Characteristics

Elemental Correlation

The results of ICP-MS chemical analysis from 23 in bedrock and hydrothermal alteration zones associated with ore bodies are presented in Table 2. From this result, the correlation coefficient between elements was calculated to identify characteristic element combinations and element groups correlated with gold.

The correlation coefficient calculation results show that typical elemental combinations include: Au-Sb (Cu, Mo, Pb, Zn, Bi, Co), Mo-Zn, Hg-Ag, and Ba-K-S. Here, Au goes with Sb, possibly with Cu, Pb, Zn, Mo, and Bi (Table 3). This result shows the transition from rock to alteration zone of Au and related elementals. From there, it is confirmed that the geochemistry shows that the samples are not at a great depth.

The tight correlation of Au with elements such as: Cu, Co, Mo, Pb, Zn, Ni, and Sb shows that the source of ore-forming matter is related to the below depth.

Table 1. Summary of Results Mineral Facies Analysis of Khauau Gold Deposit

Samples	Texture	Structure	Au	Ars	Cpy	Gn	Gra	Lim	Py	Pyh	Rut	Sph	G
KA.137	Euhedral-granular, allomorphism	Disseminated ore		Few grain	Little				1		Few grain		98
KA.165	Euhedral-granular	Disseminated ore				Little			19				80
KA.165/2	Euhedral-granular	Disseminated ore, pocket	3 grain		Little	Little		Little	3-4				95
KA.2034/1	Euhedral-granular	Disseminated ore, pocket							50		Few grain	Little	50
KA.2034/2	Euhedral-granular	Disseminated ore		Few grain					24-25				75
KA.3001	Euhedral-granular, allomorphism	Disseminated ore	3 grain	35	Little			1	2	Little	2	15	45
KA.3001/1	Gel mineral	Infilling						1					98
KA.3002/2	Euhedral-granular	Disseminated ore, infilling						ít	Few grain				99
KA.3002/3	Euhedral-granular, gel mineral	Infilling							Little				99
KA.3004	Euhedral-granular	Massive		Little					85				15
KA.3004/1	Euhedral-granular, allomorphism	Pocket, disseminated ore,		60	Little		Little		4-5				35
KA.3004/2	Euhedral-granular, allomorphism	Disseminated ore, pocket		12	Little				3				85
KA.3004/3	Euhedral-granular, allomorphism	Vein, disseminated ore,			Little				5			1	94
KA.3005	Euhedral-granular	Disseminated ore					ít	4	4		Few grain		>90
KA.3005/1	Euhedral-granular, gel mineral	Pocket, disseminated ore,						1-2	1				98
KA.3005/2	Euhedral-granular	Disseminated ore		23	Little				2				75
KA.3020/3	Euhedral-granular	Band-ore, directional		5					25				70
KA.3020/4	Euhedral-granular	Pocket, vein, disseminated ore							~35				~65
KA.3022/1	Euhedral-granular	Disseminated ore		1				2	10		Little		85
KA.3025/1	Euhedral-granular	Disseminated ore			Little		Little		9		Few grain		90
KA.3025/2	Euhedral-granular, gel mineral	Disseminated ore					Little		1	Little	Few grain		98
KA.3025/3	Euhedral-granular, allomorphism	Disseminated ore, pocket	2 grain	4	Little				Little		Few grain	1	94
KA.3026/1	Euhedral-granular	Disseminated ore							8-10		Few grain	Little	90
KA.3026/2	Euhedral-granular	Disseminated ore							2-3		Few grain		96
KA.3026/3	Euhedral-granular, allomorphism	Disseminated ore, pocket			Little		Little		3-4			Little	95

Note: (Au-Free gold, Ars-Arsenopyrite, Cpy-Chalcopyrite, Gn-Galena, G-Gangue, Gra-Graphite, Lim-Limonite, Py-Pyrite, Pyh-Pyrrhotite, Rut-Rutile, Sph-Sphalerite, 90-*Content %)*

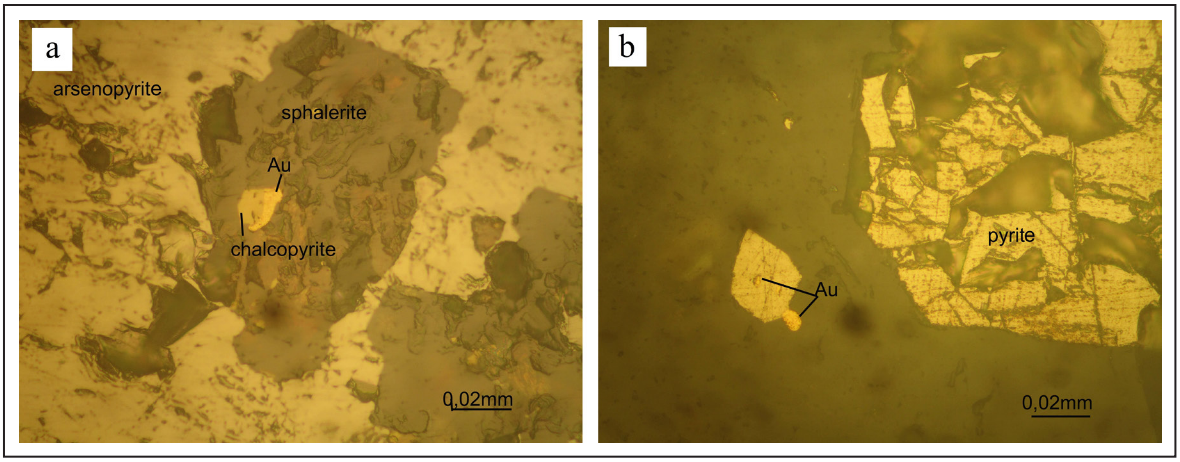

Figure 2. (a) Native gold combined with the pyrometallic sulfur combination (phase 2) of sample KA.3001, and (b) native gold concentrated into small pocket-shaped, granulated polymorphic with pyrite (phase 3) of sample KA.165/2.

Table 2. Results of ICP-MS Chemical Analysis of Rock Samples in The Khauau Gold Deposit

Sample	Au	Ag	K	As	Ba	Bi	Cu	Co	Cr	Hg	Mo	Ni	Pb	Sb	Zn	Sn	S
	gram/ton		%	ppm													
KA.100	0.18	0.30	0.12	450.59	70.79	0.36	45.65	3.28	867.22	8.94	2.00	33.36	2.55	6.29	83.94	4.32	10.11
KA.101/2	0.30	0.42	0.09	390.34	30.81	0.20	163.23	3.81	679.26	3.95	1.46	27.99	0.32	3.79	16.76	3.59	4.40
KA.102	0.27	0.63	1.77	199.97	507.11	0.40	14.35	9.56	70.73	15.26	0.10	14.95	2.73	4.41	26.03	8.38	72.44
KA.108	0.08	0.45	1.61	31.97	342.67	1.07	31.97	2.07	391.28	2.55	0.42	15.84	0.81	4.68	21.19	75.17	48.95
KA.112	0.08	0.44	1.91	109.45	630.14	0.42	109.45	2.33	385.70	2.67	0.56	24.28	4.59	4.74	51.80	10.61	90.02
KA.120	0.22	0.73	3.24	101.90	1.068.88	2.40	101.90	6.74	115.43	4.35	1.57	25.24	17.22	13.24	78.73	74.37	152.70
KA.128	0.14	1.05	1.93	30.57	548.45	0.75	30.57	2.63	229.39	2.44	1.16	19.18	19.65	3.50	57.87	34.83	78.35
KA.130	0.15	0.49	2.71	32.85	952.97	1.35	32.85	2.54	228.61	6.15	1.38	25.25	22.45	7.79	68.95	31.66	136.14
KA.136	0.47	0.82	6.17	64.15	1.899.62	2.61	64.15	32.01	187.86	9.11	1.27	41.48	38.52	3.77	63.63	34.57	271.37
KA.139	0.12	0.43	2.49	54.62	807.44	1.14	54.62	13.44	150.19	5.86	2.21	51.98	24.26	2.39	113.50	12.08	115.35
KA.140	0.39	0.76	3.57	28.52	771.02	0.64	28.52	15.82	94.56	23.56	0.76	18.64	3.54	6.02	38.13	19.21	110.15
KA.143	0.39	1.04	1.13	46.68	304.34	0.51	46.68	19.01	80.92	28.09	0.91	27.57	3.17	2.46	45.65	15.11	43.48
KA.145	0.19	0.34	2.01	57.95	688.18	0.91	57.95	8.32	191.03	7.20	0.95	31.56	27.17	5.90	47.63	18.04	98.31
KA.159	0.13	0.41	2.61	22.07	657.27	0.35	22.07	22.47	120.77	30.14	0.54	30.50	5.44	3.56	26.91	10.25	93.90
KA.162	0.89	0.67	2.71	60.73	849.12	1.63	60.73	8.96	237.25	12.48	2.66	69.55	22.54	10.72	132.88	17.57	121.30
KA.164/1	0.42	0.27	4.00	83.74	1.411.08	1.60	83.74	15.95	255.47	8.18	2.48	38.29	20.37	6.29	124.14	17.20	201.58
KA.3002/3	0.21	0.32	2.55	84.42	825.05	1.36	84.42	10.62	283.89	4.76	1.30	36.47	23.05	7.96	64.78	15.81	117.86
KA.3004	0.25	0.49	1.88	55.19	428.13	1.38	55.19	17.30	872.88	3.37	3.26	55.25	10.07	6.40	162.85	12.98	61.16
KA.3005	0.11	1.30	1.09	56.12	276.30	0.67	61.18	15.14	1.088.8	2.73	1.15	84.57	30.49	4.62	56.43	7.11	39.47
KA.3020/1	0.55	0.54	3.62	67.19	1.073.31	1.14	67.19	11.94	327.26	3.66	2.25	43.24	32.14	10.55	112.73	16.42	153.33
KA.3022	1.31	0.64	0.71	92.88	217.58	4.45	92.88	36.89	705.36	5.69	2.78	42.68	44.21	237.99	138.76	12.88	31.08
KA.3025	0.33	3.24	2.28	30.28	510.44	1.30	30.28	35.10	118.05	48.46	1.42	36.25	21.57	8.58	71.22	12.94	72.92
KA.3026	0.37	0.70	0.84	56.09	185.95	6.48	56.09	49.09	263.62	5.46	0.77	57.13	6.49	9.12	38.44	9.11	26.56

Table 3. Correlation of Element Content in The Khauau Gold Deposit Mineralization Zone

	Au	Ag	K	As	Ba	Bi	Cu	Co	Cr	Hg	Mo	Ni	Pb	Sb	Zn	Sn	S
Au	1																
Ag	-0,04	1															
K	-0.08	0,16	1														
As	-0.09	-0,31	-0,53	1													
Ba	-0,01	0,01	**0,97**	-0,39	1												
Bi	**0,53**	-0,09	-0,31	-0,26	-0,30	1											
Cu	**0,63**	-0,44	0,06	-0,07	0,24	0,33	1										
Co	**0,51**	0,42	-0,18	-0,37	-0,24	**0,85**	0,16	1									
Cr	-0,03	-0,31	-0,53	0,38	-0,48	-0,27	0,17	-0,31	1								
Hg	-0,02	**0,92**	0,15	-0,09	0,08	-0,11	-0,48	0,36	-0,46	1							
Mo	**0.52**	-0,17	0,07	0,19	0,11	-0,07	0,41	0,02	0,41	-0,09	1						
Ni	-0,03	0,11	-0,15	-0,20	-0,14	0,16	0,27	0,31	**0,54**	-0,20	0,13	1					
Pb	**0,70**	0,19	0,27	-0,31	0,35	0,10	**0,70**	0,27	0,08	0,04	0,37	0,34	1				
Sb	**0,93**	-0,09	-0,31	-0,03	-0,24	**0,46**	**0,62**	0,39	0,16	-0,09	0,43	-0,05	**0,64**	1			
Zn	**0,54**	-0,14	0,13	0,08	0,16	-0,04	0,43	0,07	0,36	-0,08	**0,99**	0,15	0,42	0,45	1		
Sn	-0,23	-0,17	0,15	-0,31	0,06	-0,17	-0,39	-0,40	-0,27	-0,16	-0,46	-0,61	-0,37	-0,11	-0,43	1	
S	-0,01	0,01	0,97	-0,39	**1**	-0,30	0,24	-0,24	0,11	-0,14	0,11	-0,14	0,35	-0,24	0,26	0,05	1

Characteristics of Geochemical Anomaly Distribution

From the results of ICP-MS analysis (Table 3), a primary dispersion halo diagram of some elements have been built to correlate with Au such as Sb, As, Cu, Pb, and Zn (Figure 3). The diagram shows the primary dispersion halos of Sb, Cu, Pb, and Zn, distributed mainly in the Khauau peak area down to Baigiang, Baimoi, and Baimo. Levell III dispersion halo with increased content of mutated elements (many times higher than the clack value) are distributed quite evenly, showing their close relationship with gold ore forming.

Characteristic Correlating Elemental Content With Ore Forming Depth

The correlation chart was built on the basis of ICP-MS analysis results for ore samples by sections from Khauau peak to Baigiang area (Table 2, Figure 4).

The chart shows the contrast in element content values at location KA.140 sample at an altitude of 778 m, the deeper down, the more element content Cu, Zn, Pb (element of the gomtallic mineral group) increases. This is the characteristic of geochemical elements of two different mineralization zones. The upper zone is a sulfur-poor mineral symbiotic with very little pyrometallic minerals. The lower zone is an increase in pyrometallic minerals such as galena, sphalerite, and chalcopyrite. Accordingly, it can be determined at a height of about 770–780 m as the dividing line between the two main ore zones in the mine area.

Forming Temperature Characteristics

Inclusions in quartz accompanying gold ore-quartz-sulfur are mainly liquid-vapour inclusions, the proportion of samples encountering vapour-liquid inclusion and vapour inclusion is very low (3/10 samples) (Table 4).

Liquid-vapour inclusions have an oval, angular, tubular shape (Figure 5a). Liquid composition is 80–90 % large, size varies from 1–8(μm) mainly 1–3(μm). inclusions homogenization temperature from 168 to 318^{o}C.

Vapour-liquid inclusions have an oval, rounde shape (Figure 5b), stable, and uniform inclusion size varying from 5–8μm, vapour phase accounts for 70–80 %, inclusions homogenization temperature is higher, varying from 305 to 410^{o}C.

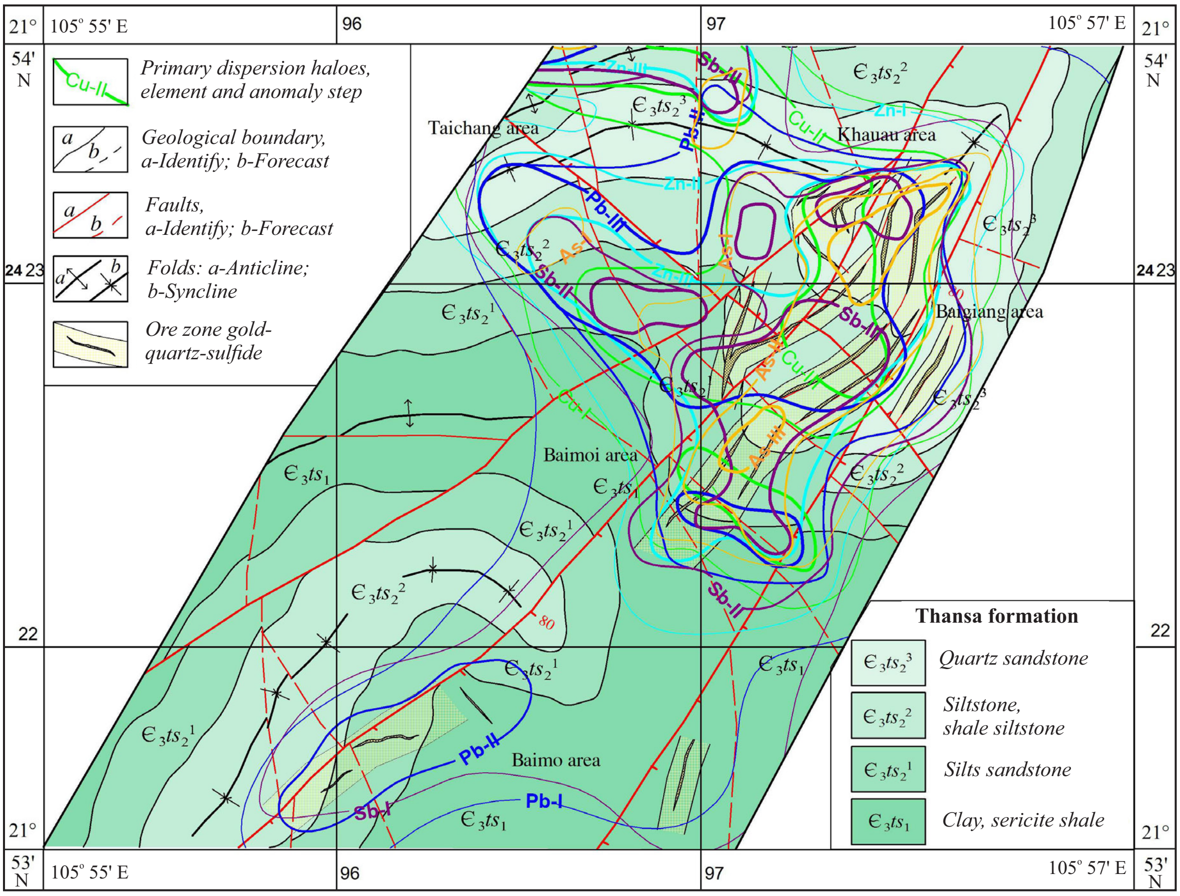

Figure 3. Distribution diagram of primary geochemical haloes and placer dispersion halos in Khauau mine area.

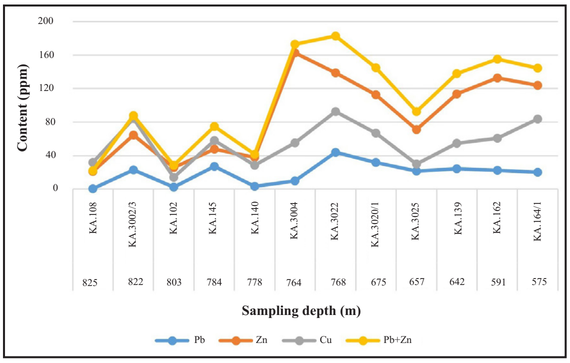

Figure 4. Correlation chart of element content of Cu, Pb, Zn groups with sampling depth.

Analytical results show that quartz has forming temperatures ranging from low to medium high, mainly belongs to the period of low average temperature, with an average of approx 240° C. Thus, gold ore-quartz -sulfur forming in the late phases of hydrothermal solution.

The results of studying the correlation between formation temperature and sample height show that they have a negative correlation (Figure 6). This is also the difference in formation temperature between the gold ore zone-quartz-pyrite poor sulfur, distributed in the Khauau peak area with an average formation temperature of 200–225°C and the gold ore zone-quartz-gomtallic distributed in the Baigiang and Baimo, and the average formation temperature is 250–270°C.

The Possibility of Ore Forming is Below Depth

The Ore-Forming Depth

The data about the ore body was determined by field investigation (Table 5). The crop ore height of the ore bodies is determined at the survey points using Garmin GPS and topographic maps. The controlled ore forming height (depth of control ore body) was determined by the mining tunnel systems and exploration boreholes meeting the ore. Based on determining the height of the denuded surface of the ore body (crop ore height) and the mineralization control height, the ore

Table 4. Summary of Inclusion Analysis Results in Quartz, Ore Gold-Quartz-Sulfur Khauau Ore Gold

No.	Sampling depth (m)	Liquid-vapour inclusion					
		Shape	Size (µm)	Components of phases (%)		Density (bt/mm^2)	Homogenization temperature (°C)
				Liquid	Vapour		
KA.100	625	Oval tubular	1-3	80-90	10-20	<50	210-295
KA.101/2	563	Oval tubular	2-3	80-90	10-20	50-100	230-310
KA.110	795	Oval tubular	1-3	80-90	10-20	<50	195-265
KA.165	721	Oval tubular	1-3	80-90	10-20	<50	205-293
KA.3002	822	Oval tubular	3-8	80-90	10-20	50-100	168-273
KA.3003	799	Oval tubular	1-3	80-90	10-20	<50	220-265
KA.3005	681	Oval tubular	1-3	80-90	10-20	<50	205-295
KA.3008	753	Oval tubular	1-3	80-90	10-20	<50	205-290
KA.3022	768	Oval tubular	1-3	80-90	10-20	<50	200-290
KA.3025	593	Oval tubular	1-3	80-90	10-20	<50	200-318
No.	**Sampling height (m)**	**Vapour - liquid inclusion**					
		Shape	**Size (µm)**	**Components of phases (%)**		**Density (bt/mm^2)**	**Homogenization temperature (°C)**
				Liquid	**Vapour**		
KA.101/2	563	rounded ovan	5-8	20-30	70-80	<50	350-410
KA.3002	822	rounded ovan	5-8	20-30	70-80	~50	335-395
KA.3008	753	rounded ovan	5-8	20-30	70-80	<50	305-380

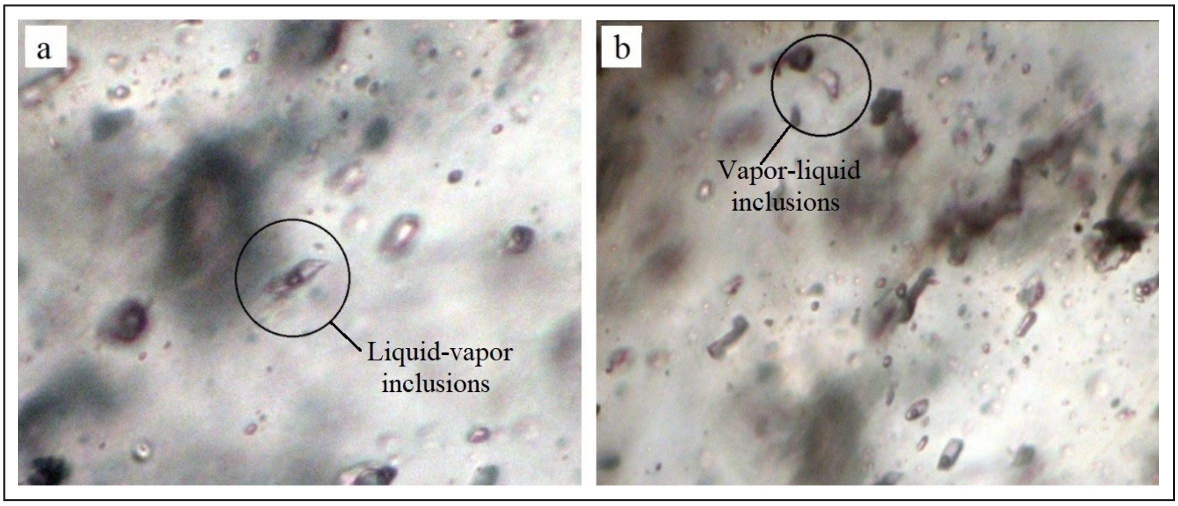

Figure 5. Image of sample KA.3008 inclusions: (a) liquid-vapour inclusions, and (b) vapour-liquid inclusions.

forming depth in the zone mine can be calculated. The calculation results are listed in Table 5.

Table 5 shows that the depth of ore bodies in the Khauau mine zone ranges from 71 m (OB16, Baimo) to 422 m (OB8, Khauau). The ore-forming depth of the Khauau region is 562 m. It is predicted that mineralization may develop to a depth of >500 m.

The Ore Body Morphology And Size

According to Lir (1984), the ratio between ore body depth in slope direction and strike line length of hydrothermal gold ore bodies has a coefficient of k= 0.6. Data on length in the strike direction and ore body size were determined by the field investigation method. According to Lir, it allows to calculate the distribution

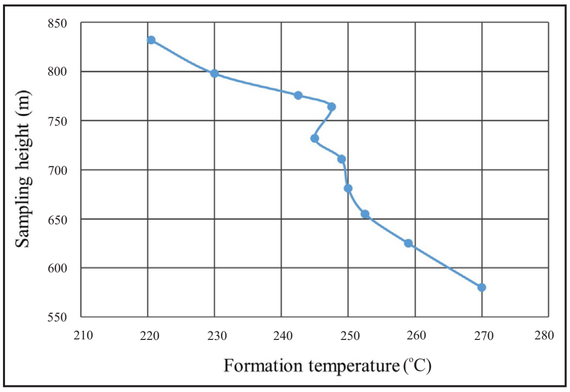

Figure 6. Inverse correlation plot between sampling altitude and ore-forming temperature.

depth of ore bodies according to slope direction (Table 6).

According to Bogaski (1982), the results of research on 243 hydrothermal vein ore bodies in southern Siberia show that the depth of development along the slope direction is nearly equal to the strike line length of the ore body, and it is true for all three types: single vein-type ore, interrupted vein-type ore, and step-shaped vein ore.

Observations in the field shows that most of the gold ore bodies of Khauau deposit have single vein-type ore, interrupted vein-type ore, and step-shaped vein ore. According to Bogaski (1982), the depth of the gold ore bodies was calculated in the Khauau deposit area (Table 6).

Calculation results show that the ore bodies in the mine zone have the potential to develop at a depth of 125-542 m. Some ore bodies have depths greater than 400 m (OB4, OB6, OB8, and OB9, Table 6).

Characteristics of Erosion of Depth

The change in vertical ore deposition conditions is one of the most important causes, related to the mineral-forming having different compositions. Calculating the zoning coefficient Kz according to (1) can evaluate the possibility of hidden deeply buried ore bodies in the studied area. Based on the ICP-MS analysis results of twenty-three samples at Khauau gold deposit (Table 3), the calculation results are shown in Table 7.

The result of calculating the zoning coefficient Kz according to Grigorian (1977) formula for the researched area is Kz= 0.3, and for ore samples is 0.83. The Kz values are all in the range of 0.1-10,000, with no Kz value < 0.1 (range below ore-erosion).

Discussion

Characteristics of Mineral Assemblage Variation

The chart of the frequency of appearance of main ore-formed minerals was built from the results of analyzing mineral facies analysis

Table 5. Range of Ore Forming Depth of Gold Ore Bodies in The Khauau Gold Deposit

No.	Area	Ore body	Crop ore height (m)	Controlled ore forming height (m)	Forecasted ore forming height (m)	Range of ore fomation depth (m)
1	Khauau	OB1	805	736	702	104
2		OB2	805	730	693	113
3		OB3	848	665	574	275
4		OB4	881	656	544	338
5		OB5	731	580	505	227
6		OB6	742	556	463	279
7		OB7	756	560	462	294
8		OB8	841	560	420	422
9		OB9	843	586	458	386
10	Baigiang	OB10	743	583	503	240
11	Baimoi	OB11	761	612	538	224
12		OB12	736	612	550	186
13	Baimo	OB13	414	359	332	83
14		OB14	380	339	319	62
15		OB15	478	430	406	72
16		OB16	439	392	369	71
Average			**700,19**	**559,75**	**489,53**	**210,66**
Range of ore forming depth of the ore field						**562**

Table 6. Existence Depth of The Gold Ores in The Khauau Gold Deposit by The Ore Body Dimension And Shape (Lir, 1984; Bogaski, 1982)

No.	Area	Ore bodies	Length in the strike direction (m)	Depth in the dip direction (m) (Lir, 1984)	Orebody order No.	Existence depth (m) (Bogaski, 1982)
1	Khauau	OB1	108,6	65,16	2	130,32
2		OB2	217,3	130,38	2	260,76
3		OB3	229,4	137,64	2	275,28
4		OB4	343,2	205,92	2	411,84
5		OB5	141,1	84,66	2	169,32
6		OB6	335,2	201,12	2	402,24
7		OB7	222,6	133,56	2	267,12
8		OB8	370,6	222,36	2	444,72
9		OB9	452,2	271,32	2	542,64
10	Baigiang	OB10	249,1	149,46	2	298,92
11	Baimoi	OB11	162,3	97,38	2	194,76
12		OB12	235,5	141,3	2	282,60
13	Baimo	OB13	189,6	113,76	2	227,52
14		OB14	103,7	62,22	2	124,44
15		OB15	131,5	78,9	2	157,80
16		OB16	202,2	121,32	2	242,64
Average			**230,88**	**138,53**	**2**	**277,06**

Table 7. Calculation of Denudation Based on The Sample ICP-MS Analysis Results in The Whole Khauau Gold Deposit

No.	Sample No.	Analysis results (ppm)						Denudation coefficient Kz
		Ag	Pb	Zn	Cu	Co	Bi	
1	KA.100	0,18	2,55	83,94	45,65	3,28	0,36	0,72
2	KA.101/2	0,30	0,32	16,76	163,23	3,81	0,20	0,01
3	KA.102	0,27	2,73	26,03	14,35	9,56	0,40	0,35
4	KA.108	0,08	0,81	21,19	31,97	2,07	1,07	0,02
5	KA.112	0,08	4,59	51,80	109,45	2,33	0,42	0,17
6	KA.120	0,22	17,22	78,73	101,90	6,74	2,40	0,18
7	KA.128	0,14	19,65	57,87	30,57	2,63	0,75	2,72
8	KA.130	0,15	22,45	68,95	32,85	2,54	1,35	2,11
9	KA.136	0,47	38,52	63,63	64,15	32,01	2,61	0,21
10	KA.139	0,12	24,26	113,50	54,62	13,44	1,14	0,40
11	KA.140	0,39	3,54	38,13	28,52	15,82	0,64	0,18
12	KA.143	0,39	3,17	45,65	46,68	19,01	0,51	0,12
13	KA.145	0,19	27,17	47,63	57,95	8,32	0,91	0,57
14	KA.159	0,13	5,44	26,91	22,07	22,47	0,35	0,11
15	KA.162	0,89	22,54	132,88	60,73	8,96	1,63	3,01
16	KA.164/1	0,42	20,37	124,14	83,74	15,95	1,60	0,49
17	KA.3002/3	0,21	23,05	64,78	84,42	10,62	1,36	0,26
18	KA.3004	0,25	10,07	162,85	55,19	17,30	1,38	0,31
19	KA.3005	0,11	30,49	56,43	61,18	15,14	0,67	0,29
20	KA.3020/1	0,55	32,14	112,73	67,19	11,94	1,14	2,19
21	KA.3022	1,31	44,21	138,76	92,88	36,89	4,45	0,53
22	KA.3025	0,33	21,57	71,22	30,28	35,10	1,30	0,37
23	KA.3026	0,37	6,49	38,44	56,09	49,09	6,48	0,01
Average		**0,33**	**16,67**	**71,43**	**60,68**	**15,00**	**1,44**	
Kz of the whole gold deposit								**0,30**
The average value of ore gold samples		**4,36**	**219,80**	**1066,82**	**553,70**	**148,03**	**15,11**	
Average Kz of ore gold samples								**0,83**

of ores samples taken at the Khauau mine area (Table 1, Figure 7). The chart indicates that high-temperature minerals, such as pyrrhotite, are almost absent. While some samples contain pyrrhotite, and its content is very low. Minerals formed at medium to medium-high temperatures such as arsenopyrite, chalcopyrite, sphalerite, and galena are more common, and most samples encountered pyrite. This indicates that mineralization in the studied area is formed at medium to medium-low temperatures. The ore being mined is mainly located in the upper part of the ore field.

According to the rules of mineral variation in hydrothermal gold ore deposits, it can be seen that from the bottom to the top the number of sulfur minerals, including carbonate minerals of Fe and Ca increases, quartz role clearly decreases, and tourmaline completely disappears. As the hydrothermal solution moves up, the temperature gradually decreases, the number of sulfur minerals participating in the ore formation process increases, and in the final stage of the ore formation process, only pyrite appears. (Smirnov *et al.,* 1983). Based on the analysis results in Table 1, a frequency chart was created to represent the distribution of the main ore-forming minerals in the Khauau gold deposit. In the chart (Figure 3) it can be seen that the number of sulfur minerals participating in the ore-forming processes is quite large, proving that the ore being exploited is located in the middle zone and above the ore field. The erosion rate here is not high. The predictions for deeply buried hidden ore bodies remain highly promising.

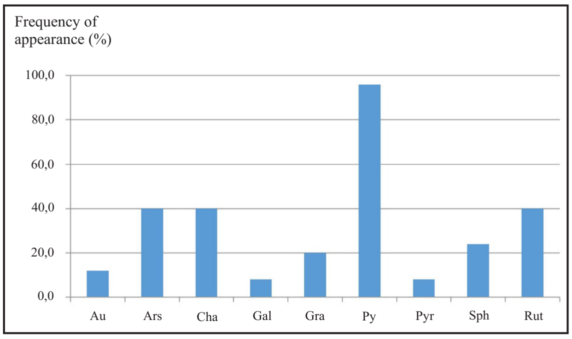

Figure 7. Frequency of appearance chart of main ore-formed minerals in the Khauau gold deposit (Au-Free gold, Ars-Arsenopyrite, Cpy-Chalcopyrite, Gn- Galena, Gra-Graphite, Py-Pyrite, Pyh-Pyrrhotite, Sph-Sphalerite, Rut-Rutile)

Zoning Characteristics of Mineralization

Vertical Zonation

Based on a research on mineral geochemical characteristics, ore-forming stages, formation temperature characteristics, and geochemical anomaly characteristics as presented above, it can be confirmed that gold mineralization-quartz-sulfur Khauau deposit is divided into three zones, which from the top to the bottom are as follows (Figure 8):

- Zone ore 1: *gold-quartz-pyrite poor sulfur.* Mineral assemblage complex: pyrite, very little chalcopyrite, sphalerite does not meet gale-

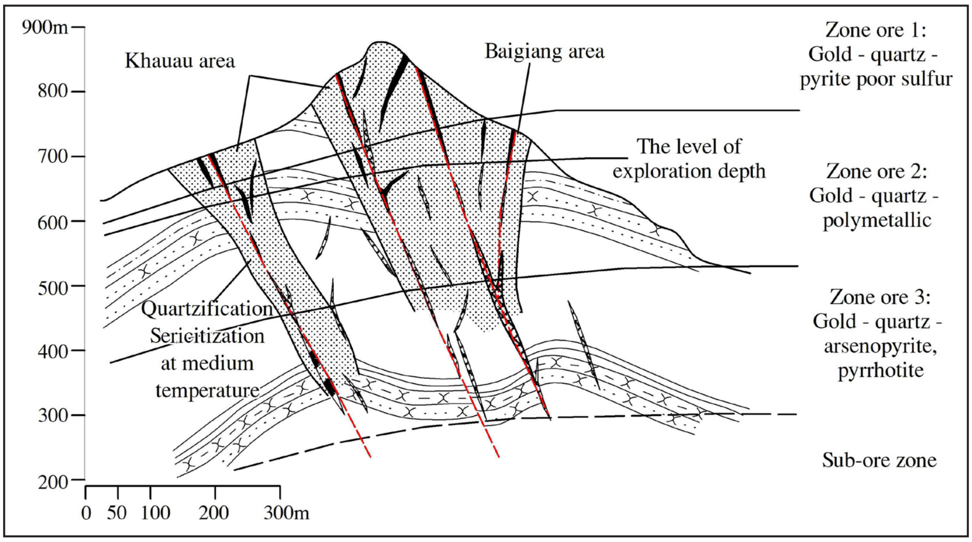

Figure 8. Cross section of gold ore zone model according to depth Khauau zone.

na. Lithostratigraphy complex includes sericitized shale mixed with siltstone, siltstone, and quartz sandstone belonging to group 2 of The Thansa Formation of Cambrian age. Average ore-forming temperature from 200 to 225^{o} C. Hydrothermal transformation includes quartzization, sericitization, and sulfurization distributed in Khauau, Baimo (Figure 9a).

- Zone ore 2*: gold-quartz-polymetallic sulfur.* Mineral assemblage complex is mainly pyrite with less sphalerite, arsenopyrite, galena, and chalcopyrite. Lithostratigraphy complex includes: sandstone, siltstone, shale, black shale containing graphite, quartz sandstone of bed 1 and bed 2 of Thansa Formation. The average ore-forming temperature is from 250 to 270^{o} C. Hydrothermal transformation includes quartzization, sericitization, berezitization, and sulfurization. Distributed in Baigiang, and in the depths of Khauau and Baimoi (Figure 9b).
- Zone ore 3: *gold-quartz-arsenopyrite, pyrrhotite.* Mineral assemblage complex is arsenopyrite which is less than pyrite and pyrrhotite. Lithostratigraphy complex includes: shale sericite, claystone, siltstone, thin layered, grey mixed with quartz sandstone. The average ore-forming temperature is from 310 to 350^{o} C. Hydrothermal transformation includes sericitization, quartzization, berezitization, and chloritization, distributed in Baigiang, Baimo, Khauau, and Baimoi.

Horizontal Zonation

The research results show that horizontal zonation develops continuously from Khauau → Baimoi → Baigiang → Baimo (Figure 8), Mineral assemblage complex is shown in Table 8 below.

Prospect Hidden Deeply Buried Ore Body

The above research results show that the development depth of gold ore bodies at Khauau gold deposits varies from 71 m to 422 m, with an average of 210.66 m. Ore-forming depth of Khauau gold deposits is 562 m. The results of calculating the depth of mineralization existence according to the morphology and the size of ore

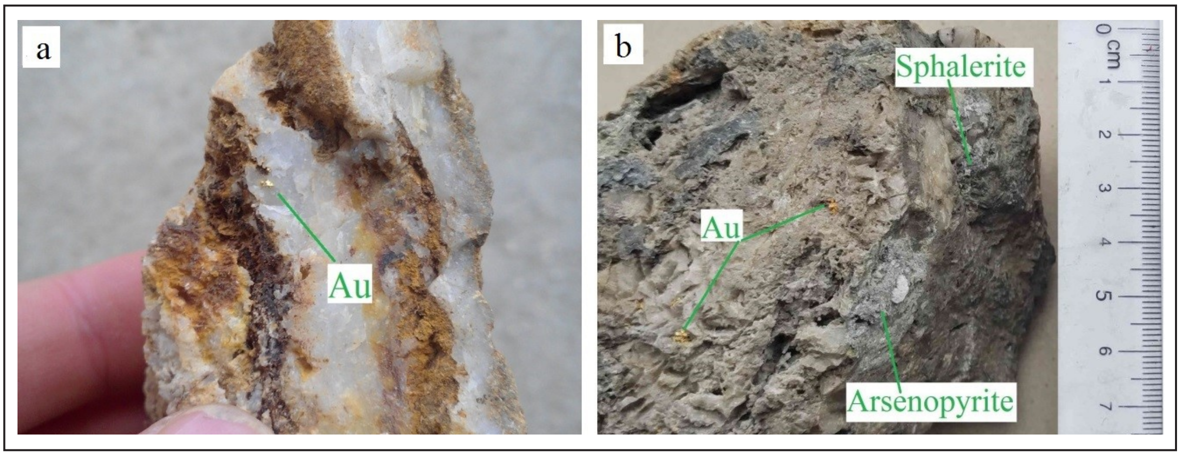

Figure 9. (a) Gold ore in gold-quartz-pyrite poor sulfur, and (b) gold ore quartz-sulfur polymetal.

Table 8. The Horizontal Zonation of Gold Ore in The Khauau Mine Area (Dat *et al*., 2020)

Location	Lithostratigraphy structure	Mineral assemblage
Khauau and Baimoi area	Shale is sericitized. Quartz sandstone, sandstone, siltstone, shale of Thansa Formation ($Є_3$ *ts*)	Quartz - gold - poor sulfur (mainly pyrite, little arsenopyrite galena chalcopyrite). Ore-forming temperature from 200 to 225^{o} C
Khauau, Baigiang, and Baimo area	Shale, sandstone, siltstone, quartz sandstone, shale, black shale containing graphite of Thansa Formation ($Є_3$ *ts*)	Quartz - polymetallic sulfur - gold, sulfur là pyrit small grain chalcopyrit, galenit, spharelit. Ore-forming temperature from 250 to 270^{o} C

bodies in the mined area are very promising at depth, with an average depth of about 277.06 m. Some ore bodies have a depth of more than 400 m, such as OB4, OB6, OB8, and OB9.

The results of calculating the zoning coefficient Kz are shown on the isometric zoning coefficient mineralization diagram (Figure 10). Figure 10 shows that the areas with low erosion rates are Khauau peak, Baimoi area, Taichang, and Khuontang areas. Among them, Taichang and Khuontang areas have not yet appeared on the surface. Along the Khauau peak extending down to Baimoi there is the ore gold-quartz- pyrite poor sulfur zone, which is an area of low mineralization erosion. Along the Khauau stream, Baigiang, and Baimo the gold ore-quartz-pyrite poor sulfur zone has been completely eroded, exposing on the surface the ore bodies of the gold ore-quartz-sulfur gomtallic zone.

Based on the distribution of mineral assemblage complexes and hydrothermal processing characteristics related to mineralization, along with the structural characteristics of the distribution of gold mineralization in the ore field of Khauau gold deposits, it can be concluded that erosion characteristic of mineralization is as follows:

Baigiang area and the lowest part of the Khauau area are mineral assemblage complex: quartz-gomtallic sulfur-gold. This shows that the mineralization of the mineral assemblage complex is quartz-gold-poor sulfur that has been eroded quite thoroughly, and has become placer gold in the Thansa and Khackiem Valleys.

The results of a research on mineralization characteristics, zonation, and the ability to exist in hidden deeply buried ore body show that Khauau gold deposits are consistent with the depth distribution model of gold deposits (Groves *et al.,* 1998) (Figure 11). According to this model, the Khauau gold ore zone is distributed at a depth of 0.5–1.2 km, and has an erosion rate of about 200–350 m.

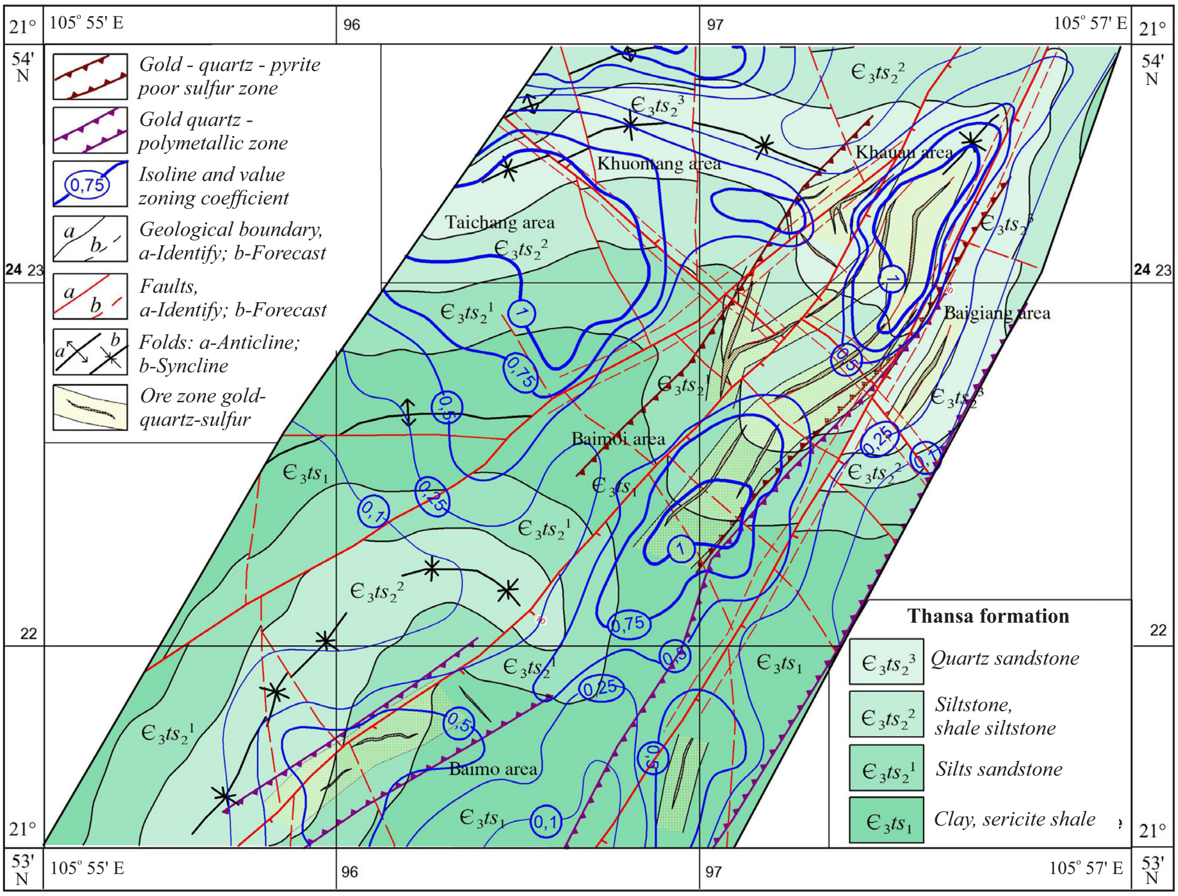

Figure 10. Zoning coefficient ore body zone isometric diagram for Khauau.

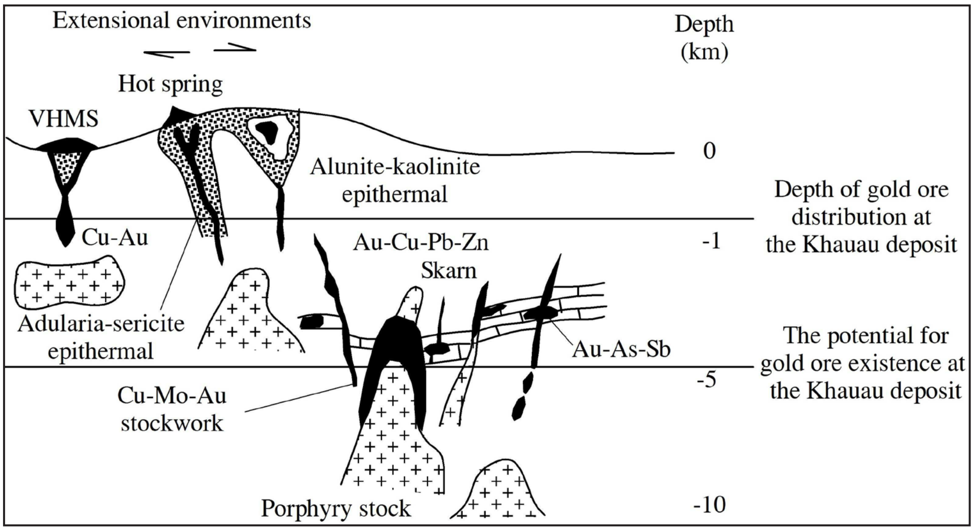

Figure 11. Model of distribution of primary gold deposits by depth (Groves *et. al*, 1998) and depth of distribution of gold ore of Khauau gold deposits.

Thus, based on the above distribution model, it can be seen that Khauau gold ore mineralization is likely to exist at a depth of 5 km.

Accordingly, it can be predicted that the Khauau gold deposits area, Binhvan commune, Chomoi District, Backan Province, will develop to a depth of >500 m. To get an accurate answer, additional verification borholes are needed.

Conclusions

Gold ore in the Khauau mine zone has medium to medium low formation temperature (168–318^o C). Gold mineralization is formed in three stages, corresponding to three mineral assemblage: gold ore-quartz -pyrite poor sulfur, gold ore-quartz-polymetallic, and gold ore-quartz-arsenopyrite, pyrrhotite. The strong correlation between Au and elements such as Cu, Co, Mo, Pb, Zn, Ni, and Sb suggests that the ore-forming solution originated from deep underground.

Research results have confirmed that in the Khauau mine zone, mineralization has the vertical zonation. From the top to the bottom it includes three zones: gold ore-quartz-pyrite poor sulfur, gold ore-quartz polymetallic, and gold ore-quartz-arsenopyrite, pyrrhotite. The ore bodies have been identified at depths ranging from 125 to 540 m, with many extending beyond 400 m. The depth of ore-forming processes is 562 m, and the zoning coefficient of Kz= 0.83. Accordingly, it is possible to predict the prospect of the Khauau gold deposit, Binhvan commune, Chomoi District, Backan Province, to a depth of more than 500 m. The depth of gold mineralization can be up to 5 km (with skarn or porphyry mines).

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