Indonesian Journal of Economic Geology (IJEG)
Volume I No. 2, September 2025: 91-113 e-ISSN 2809-1094

GOLD CHARACTERISTICS AND THEIR INFLUENCE ON THE ORE EXTRACTION PROCESS OF OXIDIZED HIGH SULFIDATION EPITHERMAL MINERALIZATION: A CASE STUDY FROM THE TUMPANG PITU DEPOSIT, EAST JAVA, INDONESIA

Nabila Anggraeni Dewi[1*], Sutarto[2], Muhammad Rio Zulfahmi[3], Imam Prasetyo[1] and Atik Setyani[1]

[1*]Department of Metallurgical Engineering, UPN "Veteran" Yogyakarta, Yogyakarta, Indonesia
[2]Department of Geological Engineering, UPN "Veteran" Yogyakarta, Yogyakarta, Indonesia
[3]Department of Adsorption Desorption Recovery, PT Bumi Suksesindo, Banyuwangi, Indonesia
*Corresponding author: 116200047@student.upnyk.ac.id

Received Date: 25 January 2025, Accepted Date: 15 July 2025, Published: 30 September 2025

Abstract

The variability of ores in mineral processing is important, as it affects process efficiency and final product quality. The inability to effectively manage this variability can lead to decreased process efficiency, increased production costs, and inconsistent product quality. This study investigates the geological and metallurgical aspects by characterizing two representative ore samples, classified as low-grade (LG) and high-grade (HG) sample with a diagnostic leaching test (DLT) and cyanidation with several methods, such as pulverized bottle roll test (PBRT), intermittent bottle roll test (IBRT), and column test (CT). Ore characterization is carried out with advanced tools, such as the Analytical Spectral Device (ASD) and Scanning Electron Microscope – Energy Dispersive Spectroscopy (SEM-EDS), to determine the mineralogy of the ore. Measurement of dissolved gold concentration was carried out by Atomic Absorption Spectrophotometry (AAS). Based on SEM-EDS analysis, the LG sample could not be identified morphologically, but the diagnostic leaching test indicated it was gravity/free cyanidable. HG samples based on SEM-EDS analysis and diagnostic leaching tests are included in the gravity/free cyanidable fraction and are present as free gold between the oxide mineral grids. The percentages of gold extraction for the LG sample using the PBRT, IBRT, and CT methods were 93.81%, 91.85%, and 84.36%, respectively. In contrast, the gold extraction percentages for the HG sample using the PBRT, IBRT, and CT methods were 94.74%, 96.19%, and 90.73%, respectively. The higher the grade of ore, the higher the gold extraction. In addition, the smaller the ore particle size, the higher the gold recovery obtained. The results can be used for the development of flow diagrams or process selection and processing optimization.

Keywords: Epithermal High Sulfidation, Gold, Leaching, Metallurgy

Introduction

The Sunda-Banda arc has a variety of dominant mineralization models, such as mineralization in northern Sumatra characterized by the Cu-Mo porphyry system and high sulfidation deposits in Miwah and Martabe. Southern Sumatra, West Java, and Central Java lack porphyry systems, but they host epithermal low-sulfidation deposits. East Java, Lombok, and Sumbawa characterized by

porphyry and epithermal sulfidation systems, such as in Tumpangpitu high-sulfidation epithermal and porphyry systems in the Tujuh Bukit Project (Hellman, 2010). The mineralization at Tumpangpitu consists of an Au-rich Cu-Au-Mo porphyry system that is overprinted by a high-sulfidation epithermal Cu-Au-Ag system. Oxidized high-sulfidation mineralization is near the surface. High-sulfidation oxidation results in the enrichment of Au, Ag, and As and the depletion of Cu (Hellman, 2010). The high-sulfidation epithermal components of the Tumpangpitu mineralization system can be divided into 4 subtypes based on oxidation intensity and metal content. The four components are fully oxidized high sulfidation, partially oxidized high sulfidation mineralization, non-oxidized and low-grade high sulfidation mineralization, non-oxidized and high-grade high sulfidation mineralization. Tumpangpitu mineral reserve data, according to the Joint Ore Reserves Committee (JORC), has gold reserves of 764 million grams in porphyry deposits and 70 million grams in epithermal deposits. PT Bumi Suksesindo carries out gold production and processing operations in Tumpangpitu. Gold processing in Tumpangpitu utilizes the heap leaching method. The selection of the heap leaching method for gold processing at PT Bumi Suksesindo is due to its suitability for ore reserves with low gold content, high porosity, and an affordable cost (Hadining, 2014).

The variability of ores in mineral processing is important, as it affects process efficiency and final product quality. The inability to effectively manage this variability can lead to decreased process efficiency, increased production costs, and inconsistent product quality. Geometallurgy is an approach that integrates geological and metallurgical information to predict geological models and mineral processing performance. Based on a review of research that has been conducted by Purwoko (2021) and Putra (2024), geometallurgical studies for Au extraction optimization have been carried out using the Intermittent Bottle Roll Test. Meanwhile, another technology that can be used to extract gold ore is the column test, which simulates heap leaching on a laboratory scale. In this study, a geometallurgical study will be carried out on oxidized high sulfidation deposits for gold extraction optimization to determine the mineralogy of the research area, the influence of grade, cyanide consumption, and the distribution of Au on the percentage of extraction.

Materials and Methods

Materials

There is one low-grade (LG) sample and one high-grade (HG) sample taken from Pit A of PT Bumi Suksesindo. The sample is prepared and reduced in size using a jaw crusher. Sampling after crushing uses the coning and quartering method.

Methods

Diagnostic Leaching Test

The diagnostic leaching test is a selective, gradual procedure for mineral leaching, followed by cyanide leaching steps to extract gold that has been liberated at each stage. The parameters used during the diagnostic leaching test are shown in Table 1.

Table 1. Diagnostic Leaching Test (DLT) Parameters

Parameter	Amount
Sample mass (g)	500
Water (mL)	750
Particle size distribution (passing 75 µm)	95%
% solid (Cyanidation)	40%
pH	10.5-11
NaCN concentration (ppm)	5000
Temp. HCl digest (°C)	50-60
HCl concentration	3 M
HCl digest duration (hours)	2
% solid (HCl digest)	33.3%
Temp. HNO_3 digest (°C)	40-50
HNO_3 concentration	20%
HNO_3 digest duration (hours)	4
% solid (HNO_3 digest)	20%
Temp. Aqua regia digest (°C)	200
AR digest duration (hours)	2

Bottle Roll Test

Cyanide leaching was performed on a sample with a P_{80} of 200 mesh in a bottle, rotated on a roller for 24 hours using the parameters in Table 2.

Table 2. Pulverized Bottle Roll Test (PBRT) Parameters

Parameter	Amount
Sample mass (g)	1000
Water (mL)	1500
Particle size distribution (passing 75 µm)	80%
% solid	40%
pH	10.5-11
NaCN concentration (ppm)	450
Leaching time (hours)	24

Cyanide leaching was performed intermittently with a sample measuring P_{100} 12.5 mm in a bottle and rotated on a roller 1 minute in 1 hour for 10 days with the parameters in Table 3.

Table 3. Intermittent Bottle Roll Test (IBRT) Parameters

Parameter	Amount
Sample mass (g)	3000

Parameter	Amount
Water (mL)	6000
Particle size distribution (passing 12,5 mm)	100%
% solid	33%
pH	10.5-11
NaCN concentration (ppm)	450
Leaching time (hours)	240
Leaching sampling time (hours)	24, 48, 72, 96, 120, 144, 168, 192, 216, 240

Column Test

The column is 2.1 meters high and 30.5 cm wide. The column is filled with ore weighing up to 277 kg, then irrigated with cyanide until the solution-to-ore ratio reaches 2 kL/ton. Every 24 hours, a sample of pregnant leach solution (PLS) is collected and analyzed for free cyanide concentration, pH, and Au, Ag, and Cu concentrations. At the end of leaching, when the solution to ore reaches 2 kl/ton, cyanide irrigation is stopped. The column is dismantled, and the ore is dewatered with an oven for 24 hours. Particle size distribution is carried out using size fractions of 45, 32, 25, 12.5, 6.7, +2.3, and -2.3, and each size fraction is weighed. The parameters in the column test are listed in Table 4.

Table 4. Column Test Parameters

Parameter	Amount
Particle size distribution	+45, +32, +25, +12,5, +6,7, +2,3, -2,3 mm
pH	10.5-11
NaCN concentration (ppm)	450 (primary leaching) 150 (secondary leaching)
Irrigation rate (L/h/m^2)	9.5 – 10

Results and Discussion

Mineralogy

The low-grade sample exhibits a dark brown, weakly vuggy texture and is strongly altered. Mineralogical characterization using ASD analysis (Table 5) indicates the presence of alunite and dickite as the principal alteration minerals, together with hematite as the dominant oxide mineral.

Table 5. ASD Analysis Result of LG Sample

Sample ID	Spectrum ID	Fe Oxide Min	Min1	Min2
LG1005	LG1005.000	Hematite	K-Na Alunite	dickite

ASD analysis was carried out on a low-grade sample to determine its mineralogy. The results of the analysis were obtained from mineralogy in the LG sample in the form of K-Na alunite and dickite, as well as oxide minerals in the form of hematite. Based on the ASD results, a low-grade sample was included in the advanced argillic alteration. Advanced argillic alteration is an alteration found in high sulfidation epithermal deposits. Oxidized and porous epithermal high deposits are ideal for extraction by the heap leaching method (Sillitoe, 2000).

The gold in the low-grade sample was not concentrated and could not be identified using BSE microscopy, as shown in Figure 1. The assay results showed that the Au in the low-grade sample was 0.4 ppm. Based on the SEM results, elemental mapping (Figure 3) has not shown a distinct pattern or a concentration of the Au element. Based on the spot analysis and the resulting percentage graph shown in Figure 2, the low-grade sample had a high O element composition. This shows that the spot or point suspected to be gold turns out to be the morphology of the oxide mineral, which appears bright in the BSE method, namely, goethite or hematite. Based on the data, the researcher suspects that the Au element is ultra-fine, as indicated by an assay value of 0.4 ppm, but cannot be morphologically identified.

The SEM test followed the research of Putra (2024), which analyzed gold using SEM with the provision of BSE magnification of 2300 times and 15kV. However, in the LG sample, gold is not visible because it is small. Agorhom (2012) used the Vertical Water Stream (VWS) as a pre-concentration technique to increase the Au content of the sample by approximately 0.01 ppm. A 20 g sample was processed in the VWS for 1 hour, and the procedure was repeated ten times to obtain a final concentrate weighing approximately 1 g. Gold recovery to the concentrate was dependent on particle size, with approximately 50% recovery for the −25 + 15 μm fraction and 70% recovery for the −30 + 20 μm fraction. The resulting concentrate was subsequently analyzed using X-ray microtomography (micro-CT). The result showed that gold particles were sparsely distributed within the sample and appeared as bright phases owing to their high X-ray attenuation coefficient. Gold grains were identified at the 1000 μm scale, although their occurrence remained relatively rare throughout the analyzed volume. The low abundance and heterogeneous spatial distribution of gold grains pose major challenges for mineralogical characterization. Consequently, a pre-concentration step is required to enrich the gold-bearing fraction before analysis. Such an approach enhances the probability of detecting and characterizing gold particles while maintaining their original surface characteristics, thereby minimizing potential biases in subsequent mineralogical investigations.

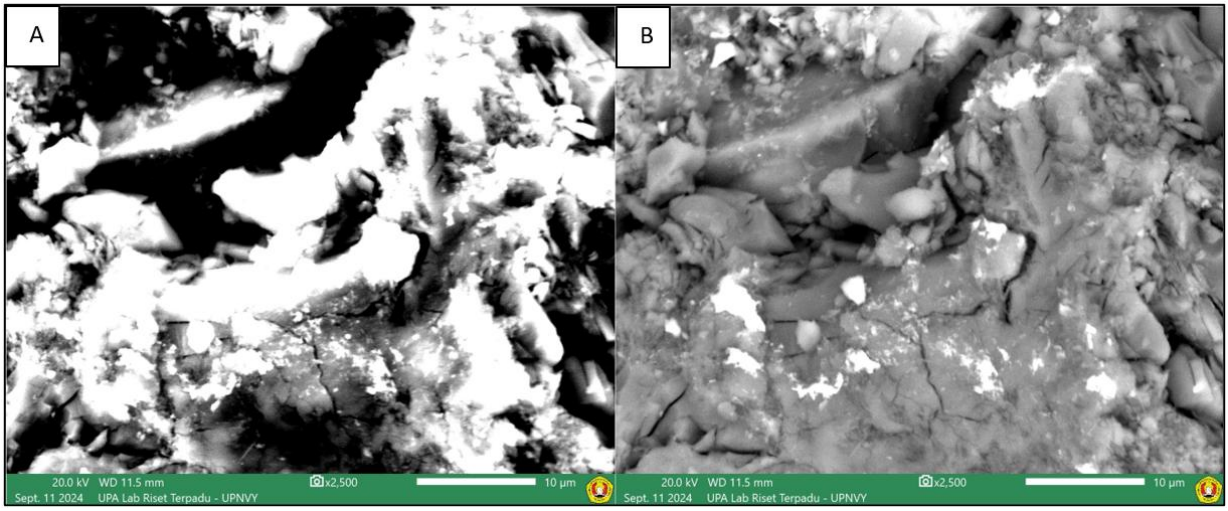

Figure 1. Morphological appearance of the LG sample of (A) scattered electrons and (B) backscattered electrons

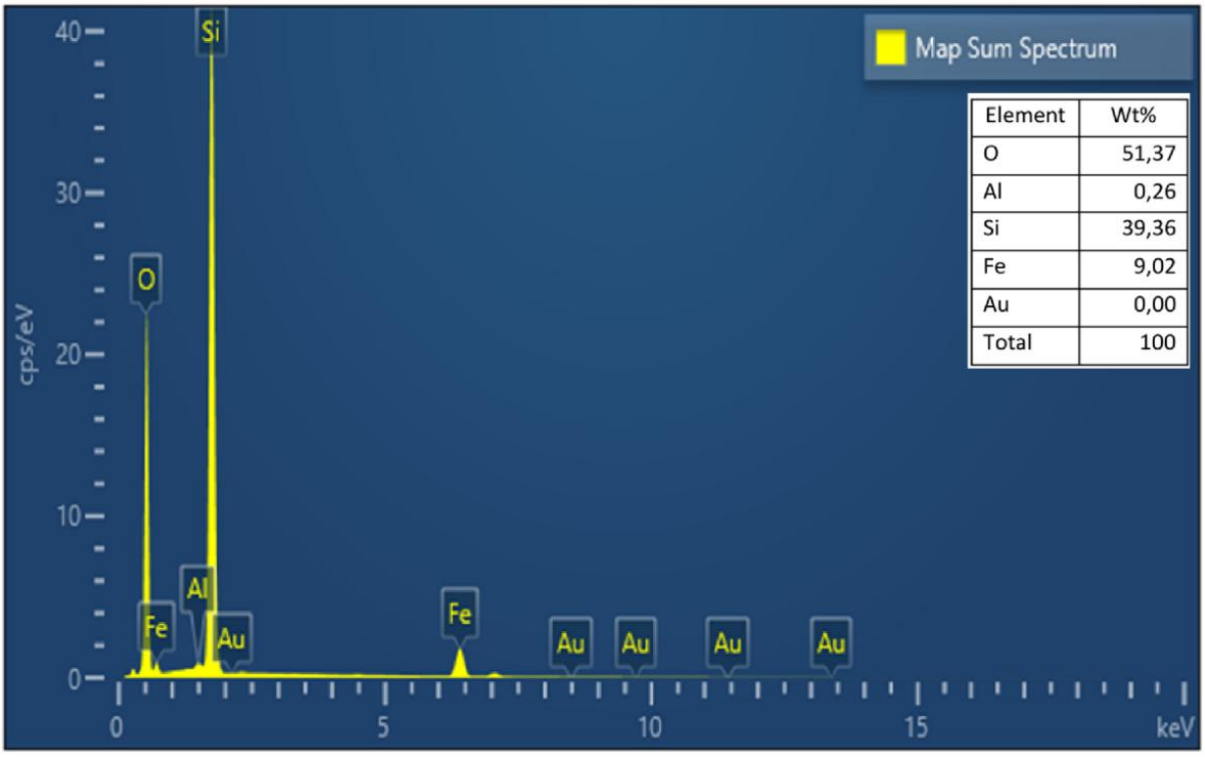

Figure 2. Diffractogram of the LG sample showing elements O, Al, Si, Fe, and Au

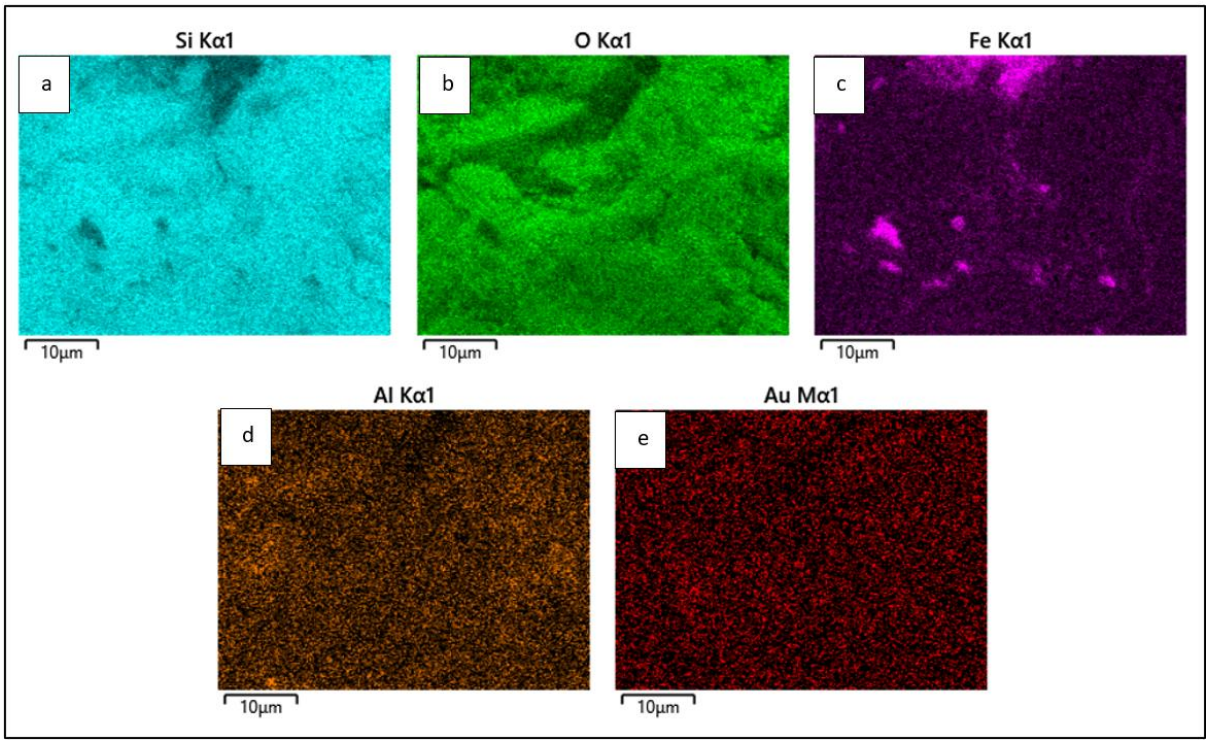

Figure 3. Elemental mapping in the LG sample: (a) silica, (b) oxygen, (c) iron, (d) aluminium, (e) gold.

Analysis using the diagnostic leaching test method was also performed to determine the sample's behaviour (Figure 4). The diagnostic leach results for the low-grade sample showed that the gold extraction in the first stage of cyanidation reached 82.3%. These results indicate that gold is mostly gravity- and free-cyanide recoverable. The cyanidation residue is then acid-leached with HCl to remove carbonate minerals; HCl can also leach calcite, dolomite, galena, and pyrrhotite (Celep et al., 2009). After that, the cyanidation process is repeated, and 9.9% gold is recovered from the carbonate. These results show the potential that needs to be further evaluated in the ore extraction process. Ultra-fine grinding is necessary to break down carbonate minerals. In addition, the flotation process can also be used to separate gold from carbonate minerals (Marsden and House, 2006). Before the flotation process, the ore is reduced in size to about 150 µm. Gold that has been liberated is floated, becoming concentrated with sulfide minerals (Teague et al., 1999). After flotation, roasting is performed to liberate the gold before cyanidation (Dunne, 2005).

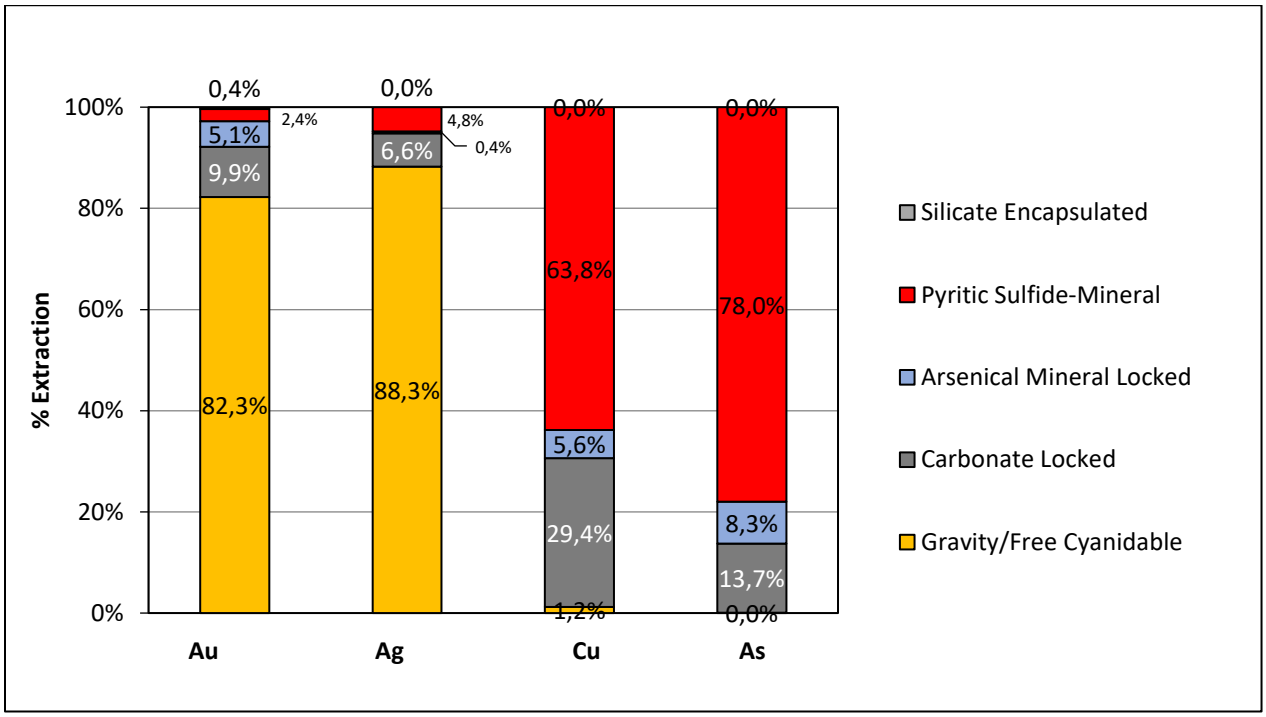

Figure 4. LG ore diagnostic leaching test (DLT) results

The residue from the second cyanidation process is then subjected to acid leaching with HNO3 to leach arsenic minerals. In addition, HNO_3 can leach pyrite, marcasite, and arsenopyrite (Celep et al., 2009). This is followed by cyanide leaching to leach gold. There is 5.1% gold included in the mineral arsenic. Gold included in arsenic minerals is referred to as solid-solution or sub-microscopic gold (Reich et al., 2005). Gold as a solid solution can be extracted by pre-treatment roasting to increase the porosity of the calcine and improve cyanidation. However, there is a pre-treatment that is more environmentally friendly than roasting, namely bio-oxidation or pressure oxidation (Coetzee, 2010).

Then, the residue from the third cyanidation process is subjected to acid leaching with aqua regia, which leaches the metals present in the pyritic-sulfide mineral. There is 2.4% gold included in the mineral pyritic sulfide. If gold is present in pyritic sulfide minerals, ultra-fine grinding is required to liberate the gold. However, this method requires a lot of energy, which will increase energy consumption. Roasting, pressure oxidation, or bio-oxidation can be alternative methods (Coetzee, 2010).

The last stage of the diagnostic leaching test is an assay that aims to determine the amount of gold metal present in the silicate. The fire assay results showed that 0.4% gold was present in silicate minerals. These results show the potential that needs to be further evaluated in the ore extraction process. Ultra-fine grinding is necessary to liberate fine gold grains from silicate minerals.

Surface passivation resulting from clay-rich and ferruginous coatings represents a major challenge in the extraction of gold from certain ore types. These coatings may partially or completely mask the surfaces of gold particles, thereby limiting contact between the mineral surface and leaching reagents. Consequently, the dissolution rate of gold can be significantly reduced. Clay minerals are particularly problematic because they tend to adhere to gold surfaces and form persistent coatings that adversely affect metallurgical performance. However, the detrimental effects of surface coatings may be mitigated through additional size reduction and attrition processes. Regrinding can remove passivating layers, increase mineral liberation, and expose fresh gold surfaces for subsequent cyanidation. In roasted ores, regrinding of calcine has been demonstrated to improve gold recovery by exposing encapsulated gold particles and eliminating soluble surface residues that may interfere with leaching reactions (Marsden and House, 2006).

Pyrite (FeS_2) is the most abundant sulfide mineral in many gold deposits and is largely resistant to dissolution under conventional cyanidation conditions. The presence of pyrite becomes particularly problematic when gold is encapsulated within or intimately associated with the sulfide phase, rendering the ore refractory to direct cyanide leaching. Therefore, an oxidation pretreatment is frequently required to decompose the sulfide matrix and expose the contained gold particles. Nevertheless, the oxidation of sulfide-bearing ores may increase reagent consumption during subsequent cyanidation. Sulfide and base-metal minerals participate in side reactions that consume cyanide, dissolved oxygen, and alkalinity, thereby decreasing process efficiency. These competing reactions can slow gold dissolution kinetics and increase the overall consumption of cyanide and lime required to achieve satisfactory gold recovery (Lestari, 2016).

Arsenic-bearing sulfide minerals, particularly arsenopyrite, realgar, and orpiment, are frequently associated with refractory gold mineralization and can significantly influence cyanidation performance. Their dissolution under alkaline leaching conditions results in the release of arsenic-containing species into solution. These dissolved species may participate in competing reactions, increasing cyanide consumption and reducing its availability for gold complexation. In addition, arsenite and arsenate species have been reported to impair gold dissolution by forming passivating surface films on gold-bearing particles. Such films restrict the transport of cyanide and dissolved oxygen to reactive surfaces, thereby reducing leaching kinetics. The accumulation of arsenic species may also alter the electrochemical characteristics of the leach environment, creating conditions less favourable for gold oxidation and, in extreme cases, substantially suppressing the cyanidation reaction (Lestari, 2016).

A dark brown colour, strong vuggy texture, and intense alteration characterize the high-grade sample. ASD analysis (Table 6) identified alunite as the dominant alteration mineral, accompanied by the iron oxide minerals goethite and hematite.

Table 6. ASD Analysis Result of HG Sample

Sample ID	Spectrum ID	Fe Oxide Min	Min1
HGS1003	HGS1003.000	goethite-hematite	K-Na Alunite

ASD analysis was performed on a high-grade sample to determine its mineralogical composition. The results of the ASD are shown in Table 6. Based on the results of the ASD analysis, the HG sample contained K-Na alunite and goethite-hematite oxide minerals. Based on the results of macroscopic observations and analysis of ASD (Analytical Spectral Device) mineral sets from a high-grade sample, the K-Na alunite was identified as part of Advanced Argillic alteration (Corbett and Leach, 1997). High sulfidation epithermal deposits rich in alunite are the most preferred gold deposits based on their gold content (high grade) in gold extraction using the heap leaching method (Bramudya et al., 2017). Oxidized and porous high-sulfidation epithermal deposits are ideal for extraction by the heap leaching method (Sillitoe, 2000; Gautama and Kusuma, 2016).

Mineralogical analysis, in addition to using spectral and ASD descriptions, was also conducted using SEM-EDX. The gold element in the high-grade sample is concentrated and can be well identified using the BSE method, as shown in Figure 5, where gold has a light colour and is depicted by forming a pattern as shown in Figure 7. Figure 6 illustrates that the Au concentration in the high-grade sample is approximately 0.08 ppm. The presence of gold in the high-grade sample is associated with the oxide minerals, as shown in Figure 7. This shows that the gold in the high-grade sample is present as free gold among the mineral oxide grid. Based on the classification of Zhou and Gu (2016), the characteristics of gold in high-grade samples are included in adsorbed gold or surface-bound gold, where gold is formed from the absorption, precipitation, and ion exchange of gold-containing solutions.

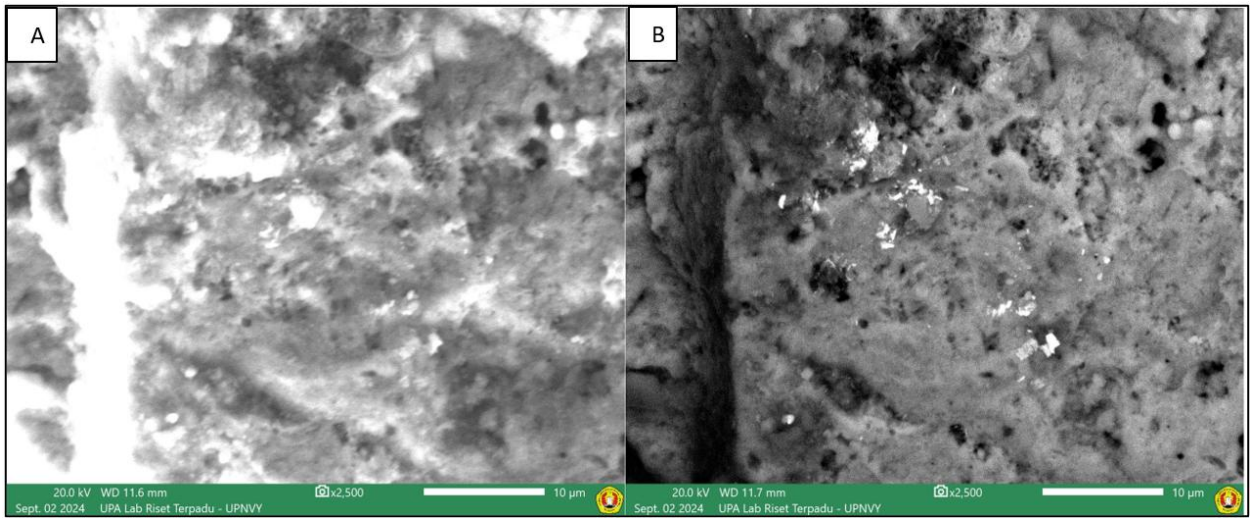

Figure … d (B)

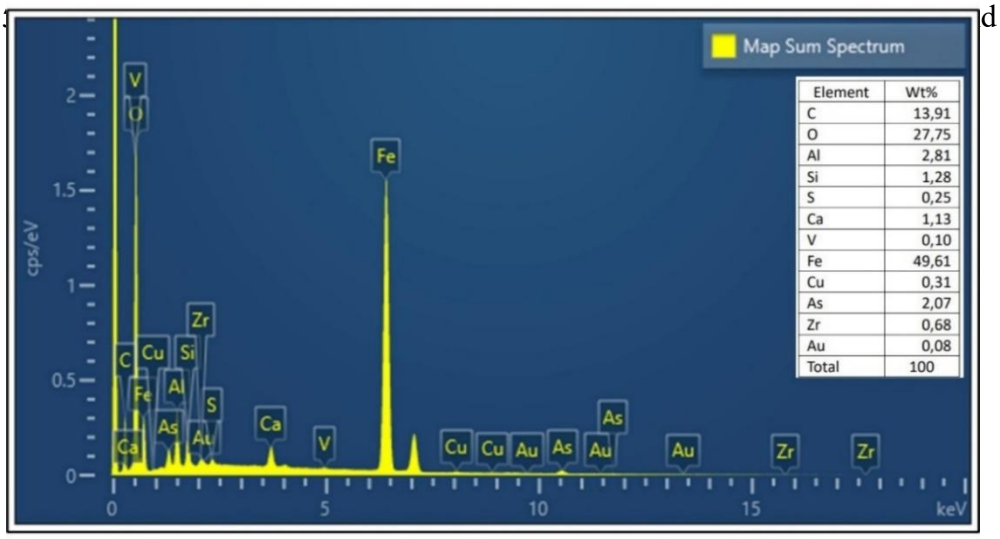

Figure 6. SEM-EDS diffractogram of HG sample

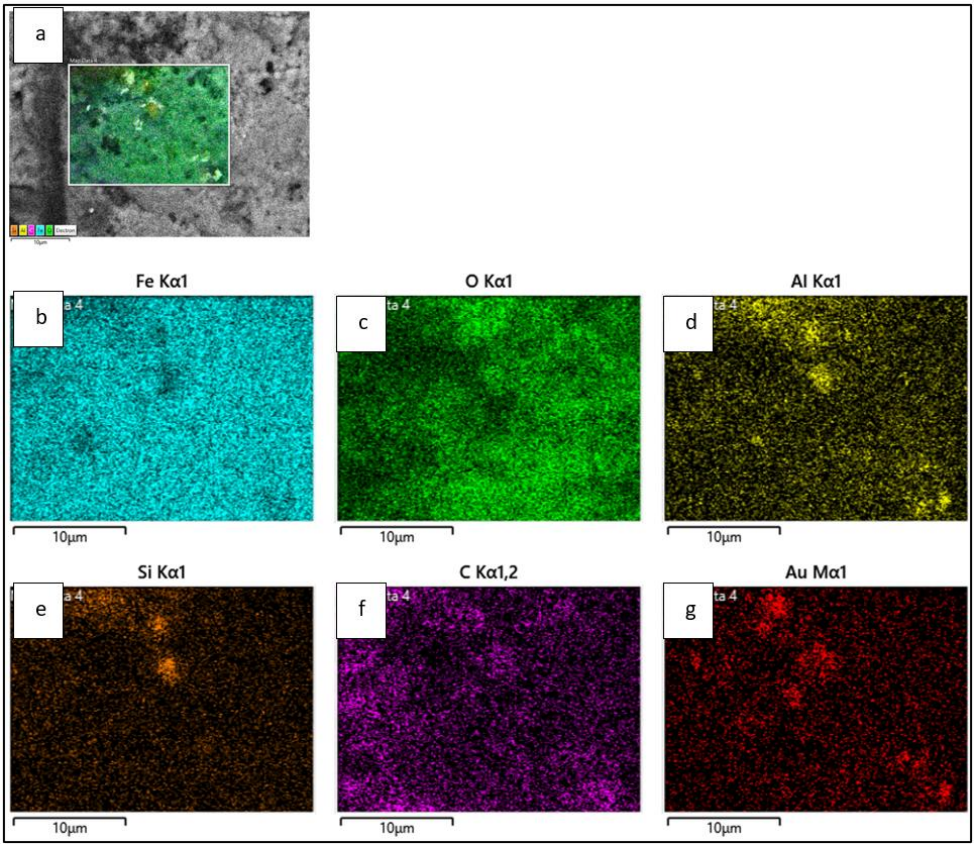

Figure 7. Elemental mapping in HG sample: (b) iron, (c) oxygen, (d) aluminium, (e) silica, (f) carbon, (g) gold.

The results of the diagnostic leach test for the high-grade ore sample are shown in Figure 8.

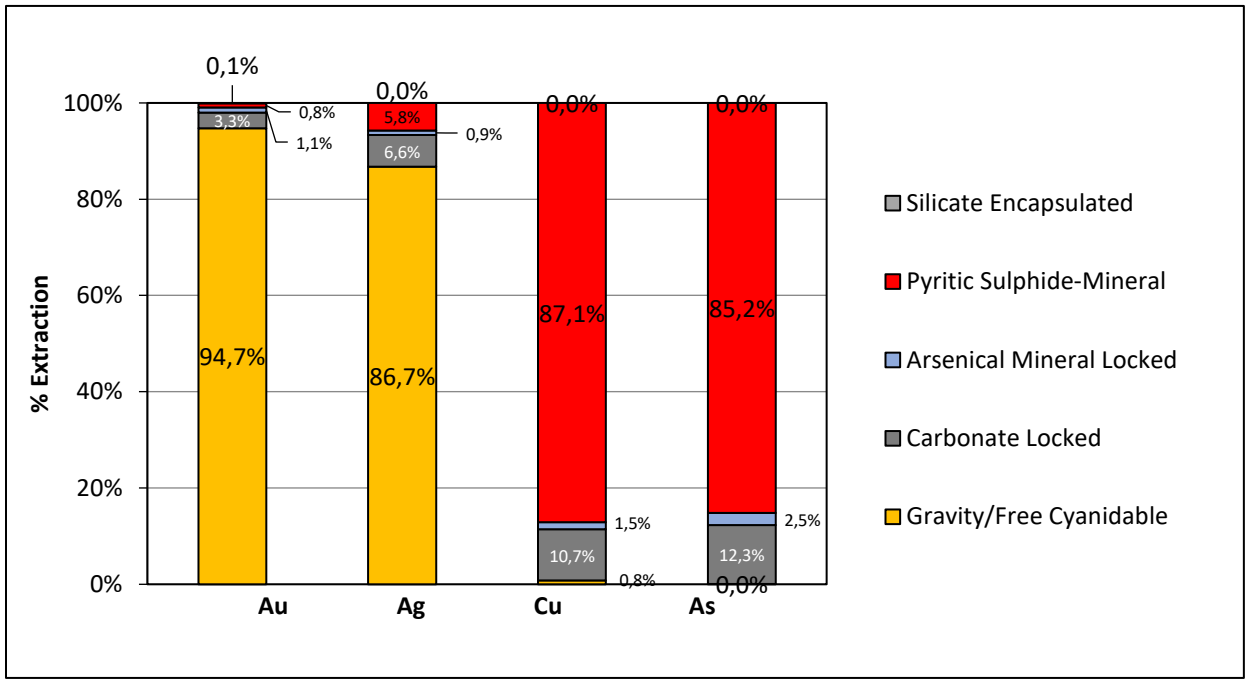

Figure 8. HG ore diagnostic leaching test (DLT) results

The high-grade sample showed that gold extraction reached 94.8% in the first stage of cyanidation. This indicates that in the ore oxide, most of the gold is gravity-free cyanidable. Then, the cyanidation residue is treated by acid leaching with HCl, which leaches carbonate minerals. In addition, HCl can leach calcite, dolomite, galena, and pyrrhotite (Celep et al., 2009). After acid leaching, the cyanidation process is repeated to recover precious metals, such as gold, previously bound to carbonate minerals. There is 3.3% gold in carbonate minerals. These results show the potential that needs to be further evaluated in the ore extraction process. Ultra-fine grinding is necessary to breakdown carbonate minerals. In addition, the flotation process can also be used to separate gold from carbonate minerals (Marsden and House, 2006). Before the flotation process, the ore is reduced in size to about 150 µm. Gold that has been liberated is flotated, and gold will become concentrated together with sulfide minerals (Teague et al., 1999). After flotation, roasting is performed to liberate the gold before cyanidation (Dunne, 2005).

The next process is acid leaching with HNO3, which leaches arsenic minerals. In addition to arsenic minerals, HNO3 can also leachate pyrite and arsenopyrite (Celep et al., 2009). After that, the third cyanidation process continued. There is 1,1% gold included in the arsenical mineral. Gold included in arsenic minerals is referred to as solid-solution or sub-microscopic gold (Reich et al., 2005). Gold as a solid solution can be extracted by pre-treatment roasting to increase the porous calcine and improve cyanidation. However, there is a pre-treatment that is more environmentally friendly than roasting, namely bio-oxidation or pressure oxidation (Coetzee, 2010).

Then the next process is acid leaching with aqua regia. Aqua regia functions to leach pyritic-sulfide minerals and is found to be 0.8% gold, included in pyritic sulfide minerals. If gold is present in pyritic sulfide minerals, ultra-fine grinding is required to liberate the gold. However, this method requires a lot of energy, which will increase energy consumption. Roasting, pressure oxidation, or bio-oxidation can be alternative methods (Coetzee, 2010).

The last stage of the diagnostic leaching test is the assay. The residue from the aqua regia process is assayed to determine the amount of gold metal present in silicate minerals. The results of the fire assay showed that 0.1% gold was contained in the silicate. These results show the potential that needs to be further evaluated in the ore extraction process. Ultra-fine grinding is necessary to liberate fine gold grains from silicate minerals.

Based on the results of the diagnostic leaching test conducted on LG and HG samples at the first cyanidation stage, the extraction percentages were 82.3% and 94.7%, respectively, for the pulverised samples. This shows that the gold in the LG and HG samples is in a free state (gravity/free cyanidable), allowing direct cyanidation without pre-treatment.

Geochemical Analysis

The Au, Ag, and Cu contents of the low-grade ore sample and the high-grade ore sample from the Tumpangpitu mine are shown in Table 7 and 8. Low-grade samples have a lower Au grade than high-grade samples. In addition to high Au, high-grade samples are also high in Cu, with levels>500 ppm.

Table 7. Low-Grade Sample

Test Method	Head Grade (ppm)			Tailing Grade (ppm)		
	Au	Ag	Cu	Au	Ag	Cu
PBRT	0,370	12,1	512	0,020	2	430
IBRT	0,380	9,3	458	0,030	5,3	487
Column Test	0,430	19,3	759	0,040	7,1	413

Table 8. High-Grade Sample

Test Method	Head Grade (ppm)			Tailing Grade (ppm)		
	Au	Ag	Cu	Au	Ag	Cu
PBRT	1,160	23,3	705	0,070	3,1	900
IBRT	1,130	13,8	763	0,050	7,9	920
Column Test	1,060	25,9	1159	0,070	11,9	701

Leaching

Bottle Roll Test

Bottle roll testing is carried out by two methods, namely pulverized bottle roll test (PBRT) and the intermittent bottle roll test (IBRT). Each used two samples, low-grade and high-grade. The test results are shown in Figure 9.

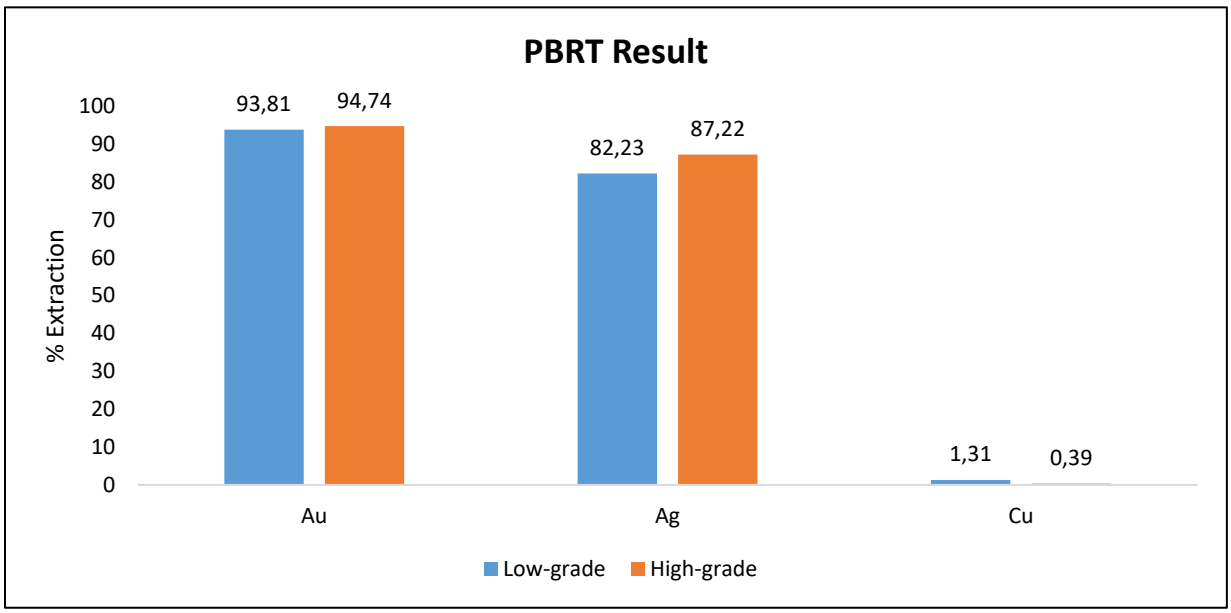

Figure 9. Pulverized bottle roll test (PBRT) result

The pulverized bottle roll test of the low-grade sample showed that the gold extraction reached 93.81%. The high-grade sample showed that gold extraction achieved a success rate of 94.74%. The PBRT method yields a higher extraction percentage than other methods. The ore sample for the PBRT method uses a pulverized or P80 size of 200 mesh and is rotated continuously on a roller. Fine particle size can increase the degree of liberation because the ore's contact with cyanide is greater, as the exposed surface area is large, leading to greater liberation and increased gain (Marsden and House, 2006).

The higher the gold ore content, the higher the extraction percentage (Ghosh et al., 2004). A high-grade sample extracted with the PBRT method has a higher extraction percentage than a low-grade sample. This is due to the difference in ore content: the low-grade sample has a level of 0.370 ppm, while the high-grade sample has a level of 1.160 ppm. This can be seen when the Au content increases; as a result, the extraction percentage will also increase. Gold extraction based on intermittent bottle-roll tests of low-grade and high-grade samples is shown in Figure 10.

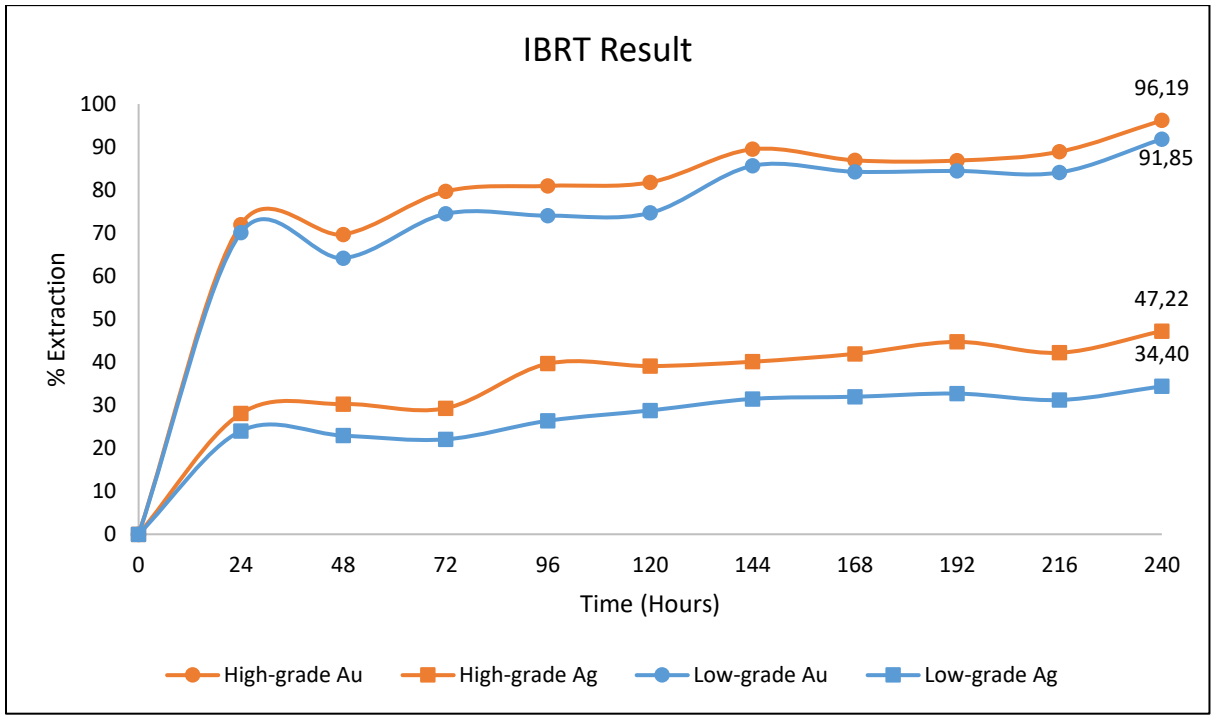

Figure 10. Intermittent bottle roll test (IBRT) result.

The percentage of extraction with the IBRT method is lower than that with the PBRT method. The results of the intermittent bottle roll test showed that gold extraction reached 91.9%. This is because the size of the ore and the rotation on the roller are different from the pulverized bottle roll test method. The ore size used in the IBRT method is P100 12.5 mm, and the rotation is 1 minute per hour. The fine particle size can increase the degree of liberation because the ore's contact with cyanide is greater, as the exposed surface area is large, leading to a higher degree of liberation and greater gains (Marsden and House, 2006). The high-grade sample for the IBRT cyanidation method had an extraction percentage of 96.19%. The percentage of extraction with the IBRT method was higher than that with the PBRT method. Based on the theory, a fine particle size can increase the degree of liberation because the ore's contact with cyanide is greater, as the exposed surface area is also large, leading to greater liberation and increased recovery. In addition, the rotation on the roller results in increased dissolution to the maximum (Marsden and House, 2006). High-grade samples obtained with the PBRT method have lower extraction percentages than those obtained with the IBRT method. This is because high-grade samples obtained with the PBRT method have an Ag content of 23.3 ppm, whereas those obtained with the IBRT method have an Ag content of 13.8 ppm. The high Ag level is what causes the extraction percentage of the high-grade PBRT sample to be lower than that of the high-grade IBRT sample. Competition for cyanide between gold and silver results in gold not consuming cyanide optimally, leading to lower extraction percentages (Marsden and House, 2006).

Column Test

The low-grade sample was cyanidated using the column test method and had an extraction percentage of 84.36% based on the back-calculated value (Figure 11). If the PBRT method uses a pulverized or P_{80} 200 mesh size and the IBRT method uses a P_{100} 12.5 mm, and both are rotated on a roller, while the column test method is carried out on a column with varying sizes, P_{100} +45 mm, P_{100} +32 mm, P_{100} +25 mm, P_{100} +12.5 mm, P_{100} +6.7 mm, P_{100} +2.3 mm, P_{100} -2.3 mm. Therefore, the extraction percentage obtained in the LG sample was lower than that of the other two methods, namely the PBRT and IBRT methods.

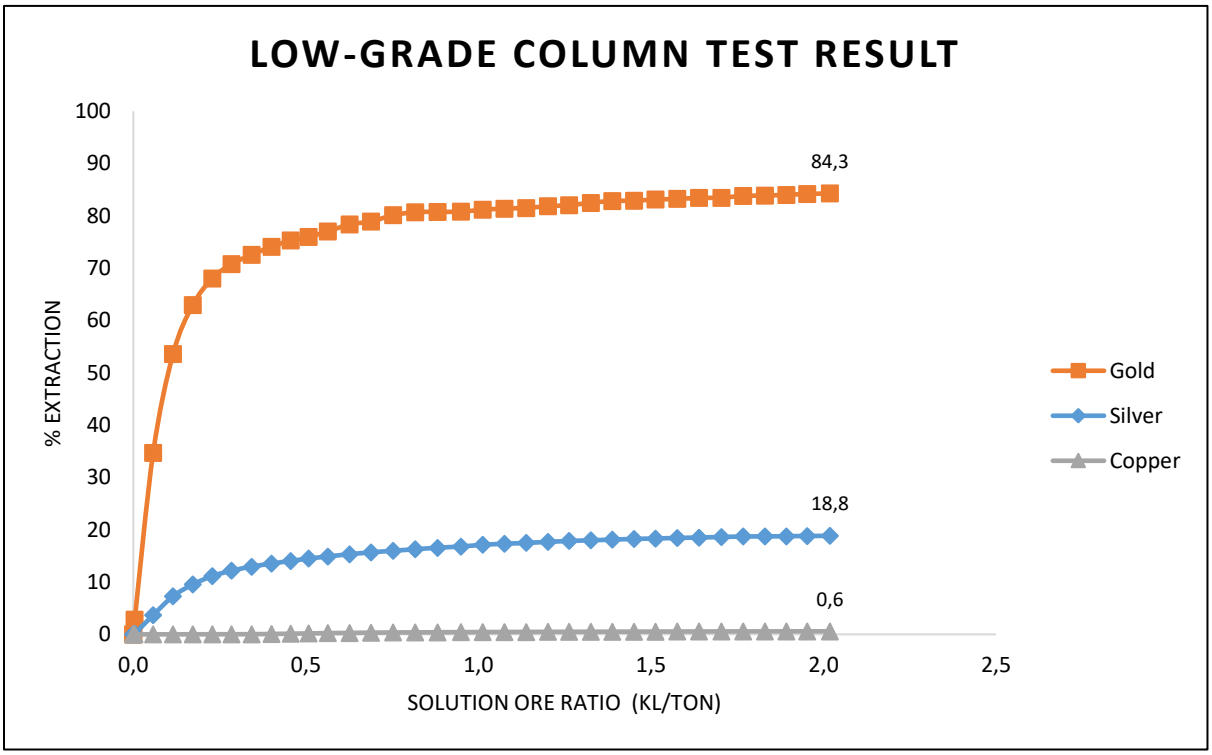

Figure 11. LG ore column test result

Low-grade ore samples have various extraction percentages. The pulverized bottle roll (PBRT) method has the highest extraction percentage value when compared to two other methods, namely IBRT and CT. This is because PBRT is a method that determines the maximum extraction percentage. The difference in the percentage of extraction obtained was due to the difference in grain size, PBRT sample used pulverized grain size, namely P_{80} 200 mesh, while the IBRT used a sample with P_{100} 12.5 mm. Fine particle size can increase the degree of liberation because the ore's contact with cyanide is greater, as the exposed surface area is large, leading to greater liberation and increased gain (Marsden and House, 2006).

Based on the results of the diagnostic leaching test at the first stage of cyanidation, which showed that the gold extraction reached 82.3%, it was not far from the results obtained in the

cyanidation process using the column test method, which reached 84.36%. This shows that most of the gold in the low-grade sample is in a gravity-free cyanidable form, allowing direct cyanidation without pre-treatment. Gold extraction based on the high-grade column test result shown in Figure 12.

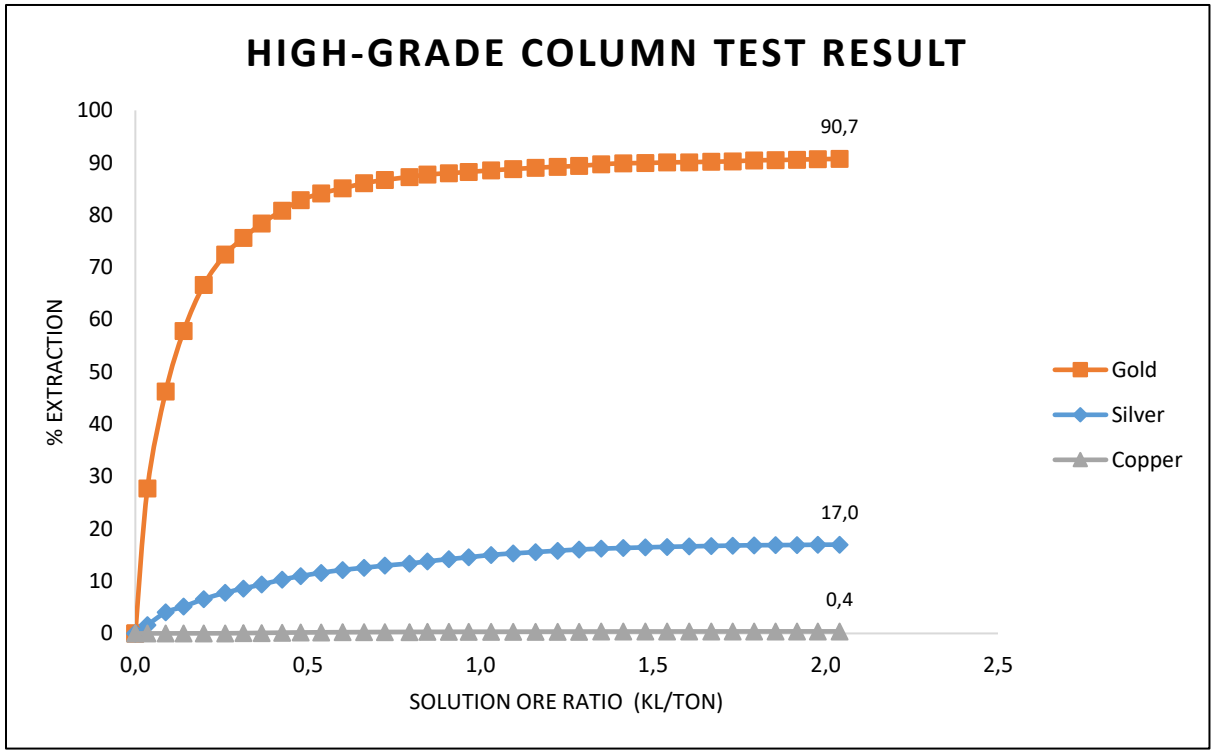

Figure 12. HG ore column test result

High-grade samples were cyanidated using the column test method and had an extraction percentage of 90.7% based on back-calculated results. If the PBRT method uses a pulverized or P80 200 mesh size and the IBRT method uses a P_{100} 12.5 mm, and both are rotated on a roller, while the column test method is carried out on a column with varying sizes, P_{100} +45 mm, P_{100} +32 mm, P_{100} +25 mm, P_{100} +12.5 mm, P_{100} +6.7 mm, P_{100} +2.3 mm, P_{100} -2.3 mm. Therefore, the extraction percentage obtained in the HG sample by the CT method was lower than that obtained by the two other methods, namely the PBRT and IBRT methods.

High-grade ore samples processed with the PBRT method have lower extraction percentages than those processed with the IBRT method. Based on function, PBRT should have a higher extraction percentage when compared to IBRT because PBRT uses a sample with fine or pulverized grain size and rotated on a continuous roller—rotation on the roller results in increased dissolution to the maximum (Marsden and House, 2006). However, the HG ore sample with the IBRT method has a higher extraction percentage than the PBRT method. In the head grade of the HG ore sample, as shown in Table 8, the HG ore PBRT has a higher Ag level, which is twice that of the HG ore IBRT sample. The high Ag level is what causes the extraction percentage of HG ore PBRT to be lower than that of HG ore IBRT. Silver consumes more cyanide, thereby increasing its extraction percentage. Competition for cyanide between gold and silver results in gold not

consuming cyanide optimally, leading to lower extraction percentages (Marsden and House, 2006).

Based on the results of the diagnostic leaching test at the first stage of cyanidation, which showed that the gold extraction reached 94.7%, far from the results obtained in the cyanidation process using the column test method, which reached 90.7%. This is due to the operating parameters used. Diagnostic leaching uses a cyanide concentration of 5000 ppm, while in the column test, the cyanide concentration is 450 ppm during primary leaching and 150 ppm during secondary leaching. In addition, from the size of the ore used, diagnostic leaching uses P_{95} 75 μm, while in the column test, it is P_{100} +45 mm, P_{100} +32 mm, P_{100} +25 mm, P_{100} +12.5 mm, P_{100} +6.7 mm, P_{100} +2.3 mm, P_{100} -2.3 mm.

The results of the first cyanidation stage in the diagnostic leaching test, with 94.7% recovery, show that most of the gold in the high-grade sample is in a gravity-free cyanidable form, allowing direct cyanidation without pre-treatment. The percentage of extraction obtained with the column test differs from that in the first stage of the cyanidation test. The result can be improved by reducing the size and increasing the cyanide concentration, based on the obtained kinetic results.

Cyanide Consumption

Cyanide consumption was calculated from the acquisition of bound cyanide and PLS pH measurement. Cyanide consumption increases or is high if the pH of the pregnant leach solution (PLS) is low; on the other hand, high pH can minimize cyanide consumption (Ling, 1996). Low-grade ore samples have a higher average pH than high-grade ore samples. Low-grade ore has an average pH of 11.79, compared to 11.52 for high-grade ore. In accordance with the theory that high pH can minimize cyanide consumption, low-grade ore has a lower cyanide consumption than high-grade ore. The cyanide consumption of low-grade ore is 0.25 kg/ton, while the cyanide consumption of high-grade ore is 0.3 kg/ton.

The high-grade sample has a higher copper content compared to the low-grade sample. The high-grade sample has a copper content of 1159 ppm, while the low-grade sample has 759 ppm. Gold leaching in cyanide solutions in the presence of sulfide minerals has shown that heavy metal components, such as Cu, Fe, and Zn, increase cyanide consumption (Habashi, 1967). The cyanide consumption of the high-grade sample is higher than that of the low-grade sample. The cyanide consumption of the high-grade sample is higher than that of the low-grade sample. In primary leaching, the free cyanide levels in the high-grade sample were higher than those in the low-grade sample. The average free cyanide content in the high-grade sample was 298 ppm, while the average free cyanide content in the low-grade sample was 295 ppm, as shown in Figure 13. In secondary leaching, the free cyanide levels in the high-grade sample were lower than those in the low-grade sample. The average free cyanide content in the high-grade sample was 61 ppm, while the average free cyanide content in the low-grade sample was 64 ppm. The high levels of free cyanide in PLS indicate that many CN- have not bonded to metals to form complex ions, so the extraction percentage obtained is lower than optimal.

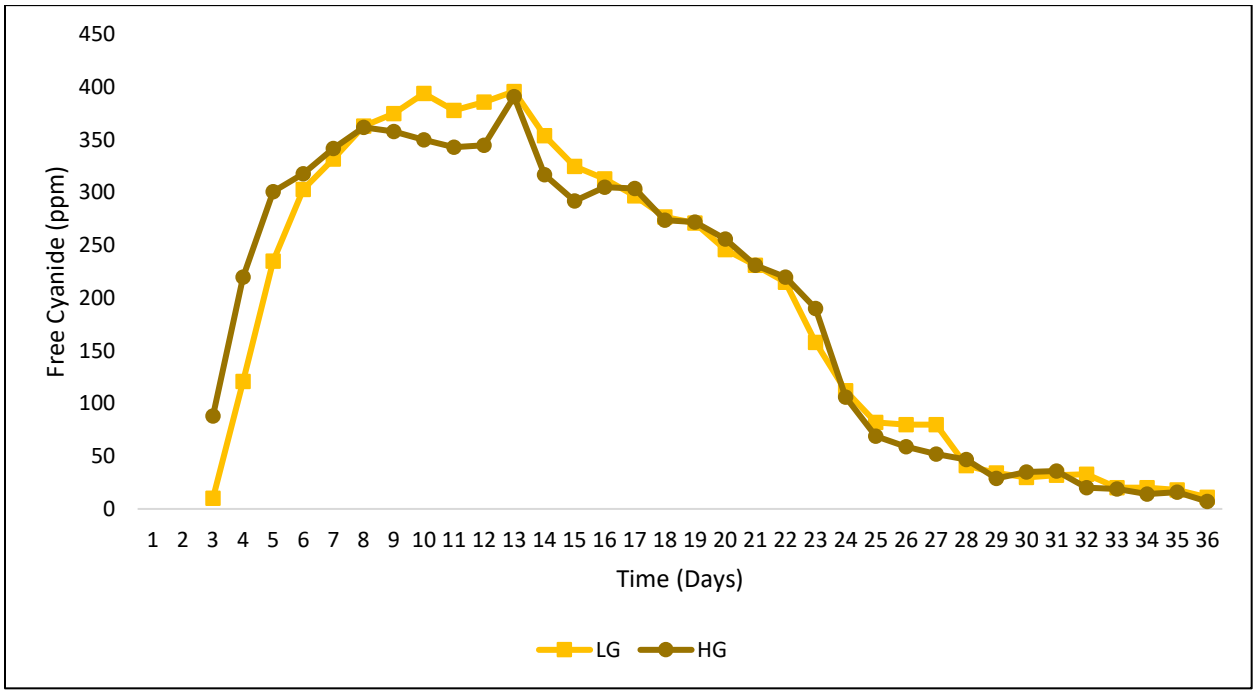

Figure 13. Free cyanide high-grade and low-grade samples

Gold Distribution Based on Size Fraction

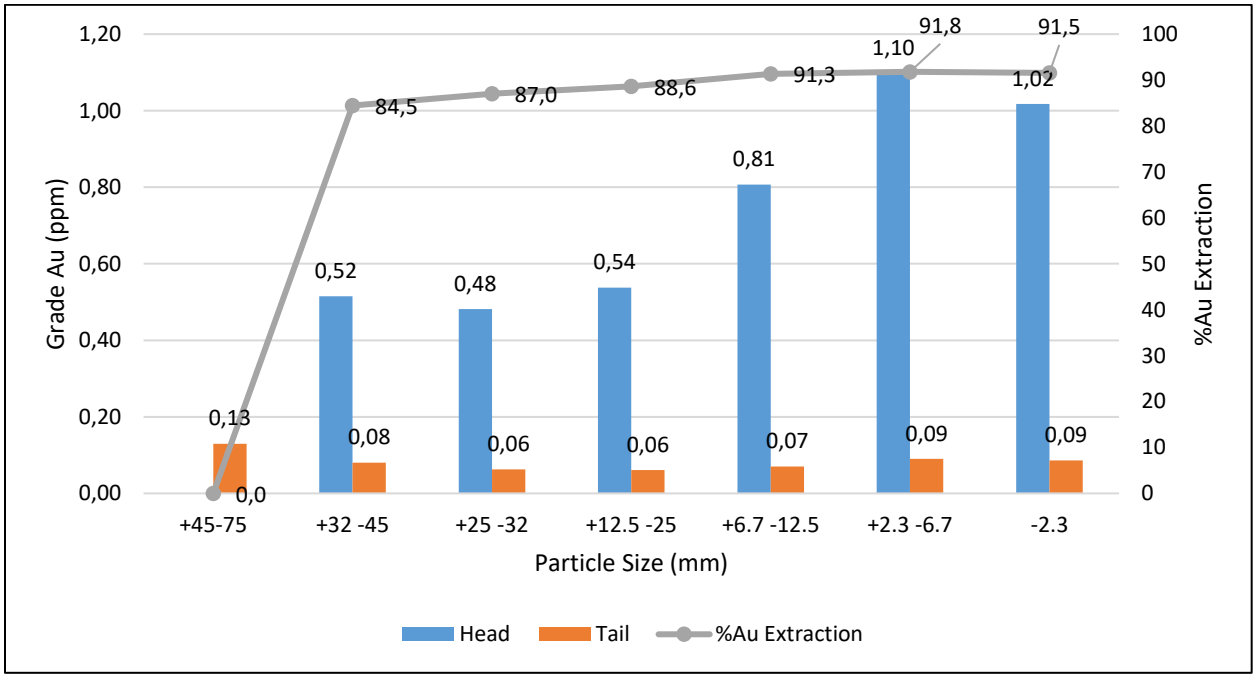

Figure 14. The LG sample gold distribution based on size fraction

The gold distribution graphs for the LG and HG samples, based on size fraction, are shown in Figure 14 and Figure 15, respectively.

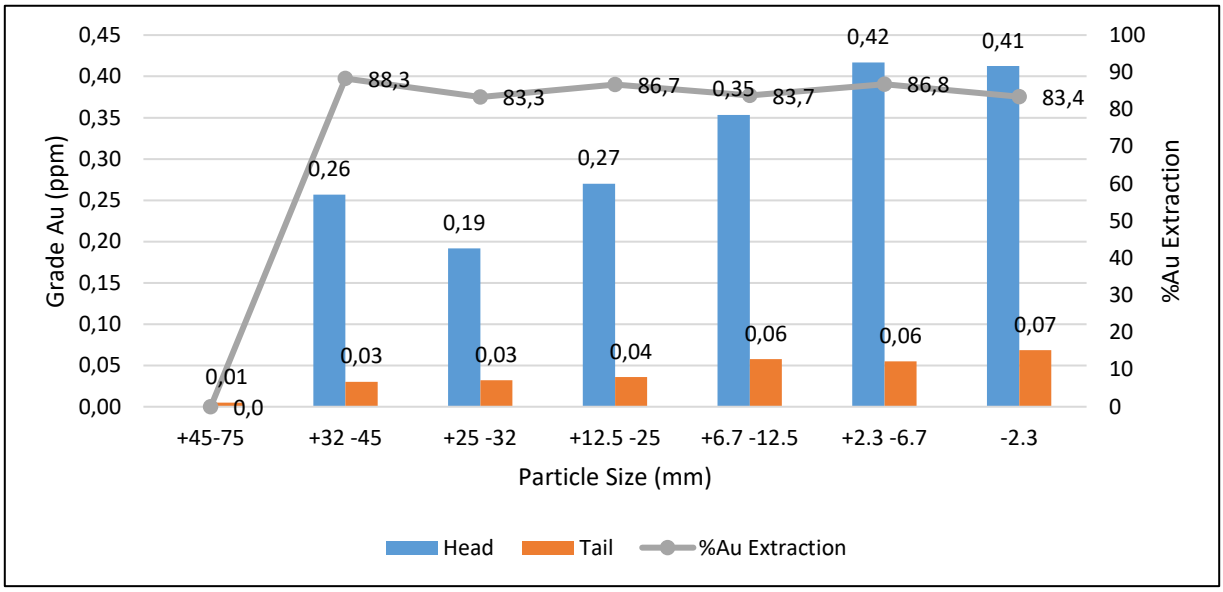

Figure 15. HG sample gold distribution based on size fraction

The exposed surface area is a function of both the particle-size distribution and the liberation characteristics of the feed material, which are largely determined by the efficiency of the comminution stages preceding leaching. Generally, finer particle sizes promote higher dissolution rates by increasing gold liberation and enlarging the effective surface area of gold particles through mechanisms such as particle flattening and fragmentation during grinding. However, this trend may not apply to ores containing significant amounts of cyanide-consuming constituents. In such systems, excessive particle size reduction can decrease the dissolution rate by accelerating competing cyanide-consuming reactions. Consequently, the optimal particle size represents a compromise between maximising gold extraction and minimizing cyanide consumption (Marsden and House, 2006).

Each fraction in the low-grade ore sample has an extraction percentage of about 80%, and the higher the extraction percentage, the smaller the ore size. In the high-grade sample, the extraction percentage is high in each fraction and increases with smaller particle size. The smaller the grain size in the HG sample, the higher the gold extraction percentage. According to Fahira (2022), the smaller the grain size during leaching, the higher the gold extraction rate. These results are in line with Fahira's research, which found that the extraction percentage increases with smaller grain sizes. The results of the study are consistent with the theory that fine particle size can increase the degree of liberation because the ore's contact with cyanide is greater, as the exposed surface area is also large, resulting in a higher degree of liberation. Also, the gain will increase (Marsden and House, 2006).

Conclusions

1. This location characterizes a high sulfidation epithermal deposition area consisting of an alteration zone: advanced argillaceous alteration (alunite + dickite)
2. The Au characteristics in the LG sample could not be identified because the size of the Au element was ultra-fine. The Au characteristics in the HG sample are in the form of adsorbed gold (surface-bound gold) and free gold within the oxide mineral matrix.
3. The results of the diagnostic leaching test showed that in the LG and HG samples at CN-1, the percentage of Au extraction in LG ore was 82.6% and in HG ore was 94.8%. The results indicate that most of the gold in oxide ore is gravity/free cyanidable.
4. The higher of a grade of ore, the higher the percentage of extraction obtained.
5. The smaller the ore size in the LG and HG samples, the higher the percentage of extraction obtained.

Acknowledgement

The author would like to extend deepest gratitude to PT Bumi Suksesindo for the opportunity to conduct this research.

References

A. Fahira, “Studi Ekstraksi Bijih Emas Kaya Tembaga PT Nusa Halmahera Minerals Pada Proses Sianidasi Dengan Metode Pulverized Bottle Rol”, *Universitas Pembangunan Nasional "Veteran" Yogyakarta*, 2022.

A. J. Teague, J. S. J. Van Deventer, C. I. Swaminathan, “A conceptual model for gold f lotation,” *Miner. Eng*. 12, 1001–1019, 1999.

A. J. Teague, J. S. J. Van Deventer, C. I. Swaminathan, “The effect of galvanic interaction on the behaviour of free and refractory gold during froth flotation,” *Inter. J. Miner. Process*. 57, 243–263, 1999.

A. Maryono, R. L. Harrison, D. R. Cooke, I. Rompo, & T. G. Hoschke, “Tectonics and geology of porphyry Cu-Au deposits along the eastern Sunda magmatic arc, Indonesia,” *Economic Geology*, 113(1), 7-38, 2018.

Adams, Mike D., ed., Advances in gold ore processing, Elsevier, 2005.

E. A. Agorhom, W. Skinner, & M. Zanin, “Upgrading of low-grade gold ore samples for improved particle characterisation using Micro-CT and SEM/EDX,” *Advanced Powder Technology*, 23(4), 498-508, 2012.

E. N. Bramudya, A. Pratama, S. A. Kowara, A. Rura, D. Pertiwi, “Ore Characterization of High-Sulphidation Epithermal Gold Deposit as Key Step for Geometallurgy in The HeapLeach Processing at Bakan,” *Proceedings MGEI Geometallurgy Convention*, p.81-84, 2017.

F. Habashi, “Principles of Extractive Metallurgy, Hydrometallurgy,” *Gordon & Breach, New York*, pp. vol. 2, 24–53, 1970.

G. Corbett, & T. Leach, "Southwest Pacific Rim Gold-Copper Systems: Structure, Alteration, and Mineralization," Australia, 1997.

H. Purwoko, "Pengaruh Liberasi Mineral Terhadap Angka Perolehan Logam Emas Pada Proses Heap Leach Area Pit C Tumpang Pitu, Kecamatan Pesanggaran, Kabupaten Banyuwangi, Jawa Timur," *UPN "VETERAN" YOGYAKARTA*, 2021.

J. C. Carlile, & A. H. G. Mitchell, "Magmatic arcs and associated gold and copper mineralization in Indonesia," *Journal of Geochemical Exploration*, 50(1-3), 91-142, 1994.

J. C. Yannopoulos, "The extractive metallurgy of gold," *Springer Science & Business Media*, 2012.

J. Marsden, & I. House, "The chemistry of gold extraction", *SME*, 2006.

J. Zhou, & Y. Gu, "Geometallurgical characterization and automated mineralogy of gold ores," *In Gold ore processing* (pp. 95-111), *Elsevier*, 2016.

K. L. Putra, "Geologi, Alterasi dan Mineralisasi Di Pit A dan Pit C Daerah Tujuh Bukit, Banyuwangi, Jawa Timur," *Universitas Pembangunan Nasional" Veteran" Yogyakarta*, 2020.

K. L. Putra, "Pengaruh Karakteristik Emas Terhadap Nilai Recovery Emas di Tambang Emas Tumpangpitu, Banyuwangi, Jawa Timur, Indonesia," *Institut Teknologi Bandung*, 2024.

L. L. Coetzee, S. J. Theron, G. J. Martin, J. D. Van der Merwe, & T. A. Stanek, "Modern gold deportments and its application to industry," *Minerals Engineering*, 24(6), 565-575, 2011.

M. Reich, S. E. Kesler, S. Utsunomiya, C. S. Palenik, S. L. Chryssoulis, & R. C. Ewing, "Solubility of gold in arsenian pyrite," *Geochimica et Cosmochimica Acta*, *69(11), 2781-2796*, 2005.

O. Celep, İ. Alp, H. Deveci, & M. Vicil, "Characterization of refractory behaviour of complex gold/silver ore by diagnostic leaching," *Transactions of Nonferrous Metals Society of China*, *19(3), 707-713*, 2009.

P. L. Hellman, "Tujuh Bukit Project Report on Mineral Resources, Located in East Java, Indonesia," *Technical Report for Interprid Mines Limited*. URL: http://media. wotnews.com.au/esxann/01120-850pdf. [Accessed: December 2024]

P. Ling, V. G. Papangelakis, S. A. Argyropoulos, & P. D. Kondos, "An improved rate equation for cyanidation of a gold ore," *Canadian Metallurgical Quarterly*, 35(3), 225-234, 1996.

R. Dunne, "Flotation of gold and gold-bearing ores," *Developments in mineral processing*, 15, 309-344, 2005.

R. H. Sillitoe, & J. W. Hedenquist, "Linkages between Volcanotectonic Settings, Ore Fluid Compositions, and Epithermal Precious Metal Deposits," *Society of Economic Geologists, Special Publication 10. London*. Hal 1-73, 2003.

R. H. Sillitoe, "Styles of high-sulphidation gold, silver and copper mineralisation in porphyry and epithermal environments," *In Proceedings of the Australasian Institute of Mining and Metallurgy* (Vol. 305, No. 1, pp. 19-34). Parkville, Vic.: The Institute,[1990]-c2001, 2000.

R. L. Harrison, "Geochronology of The Tumpangpitu Porphyry Gold-Copper Molybdenum And High-Sulfidation Epithermal Gold-Silver-Copper Deposit - Evidence For Pre And Post-Mineralization Diatremes In The Tujuh Bukit District, Southeast Java, Indonesia," *Economic Geology (in press)*, 2017.

R. Lestari, "Sulfide Processing," 2016.

R. S. Gautama, & G. J. Kusuma, "Characterization of Acid Producing Potential of Spent Ore from Heap Leach Plant," 2016.

R. S. Ghosh, D. A. Dzombak, and G. M. Wong-Chong, "Physical and chemical forms of cyanide, cyanide in water and soil, chemistry, risk, and management," *Taylor and Francis*, 15-25, 2006.

W. N. Hadining, "Laporan Kerja Praktik Proses Pengolahan Emas dengan Metode Heap Leaching PT J Resources Bolaang Mongondow," *Institut Teknologi Bandung*, 2014.